ARM POSTURE AND HAND MECHANICAL IMPEDANCE IN THE CONTROL OF A POWER DRILL

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SUBMITTED TO THE
DEPARTMENT OF MECHANICAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
January 30th, 1995

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Submitted to the Department of Mechanical Engineering on January 30th, 1995
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Mechanical Engineering

ABSTRACT

This research investigated the control of a hand-held power drill by human operators. A better understanding of human performance in this context may be helpful for the automation of industrial processes, or to prevent occupational disorders such as Carpal Tunnel Syndrome or Hand-Arm Vibration Syndrome. We chose to investigate the control of a drill by analyzing the upper limb posture and hand stiffness of drill operators.

We found that posture was repeatable within a subject, that it was insensitive to both the level of axial force exerted and the drill length. In addition, posture was similar while drilling or pushing on the drill when turned off. These results suggest that upper limb kinematics is an important factor. However, neither maximization of hand manipulability nor isotropy characteristics of a 2D two link model could explain the posture selected by subjects. Instead, minimization of joint torques appeared plausible. Right handed subjects selected a posture that minimized shoulder torque, in contrast to left handed subjects who selected a posture that minimized elbow torque.

We have developed a model to demonstrate how hand stiffness can be used to compensate for the static instability induced by the axial force exerted on a drill handle. As hand stiffness could not be measured directly while subjects were drilling, it was measured while they were asked to push on a drill handle mounted on a pivoting stick. Results showed that subjects did more than simply compensate for the static instability; hand stiffness either remained constant or increased with force. We found no evidence that one would voluntarily modulate his/her hand stiffness to fulfill some criteria. Stiffness increase may just be a well-tuned side effect of muscle activation.

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ACKNOWLEDGMENTS

This work was made possible by the financial help of the "Institut de Recherche en Santé et Sécurité au travail" of Québec, Canada; funding was also provided by NIH, grant no. AR-40029.

Because of his unconditional and constant support, patience, joy of learning, good critics and great knowledge, Neville Hogan, my supervisor, has been an important companion all along this research. My committee, Neville, Sandro Mussa-Ivaldi, Will Durfee and Thomas Sheridan has also been very patient during all those committee meetings. Thank you for your understanding and help.

I am particularly grateful to Pat Lord. Pat has been a necessary element in this research. Most of the computer facilities and software that were used in this study originated from Pat's work. He made my life a lot easier and allowed me to focus on other issues which were more relevant to motor control. Other members of the lab have obviously been an important part of my life, either socially or professionally. Thank you to all of you. I wished I had more time to meet you, but time was a critical issue toward the end... Discussions with Ted, Tony, Justin, Joe, Igo, and Ernie have been quite useful in the course of my work.

Secretaries from the mechanical engineering department were also very helpful when administrative difficulties showed up. Thank you Leslie for all your affection and efforts to put some life into this mechanistic environment.

Despite the fact that my family was away from me during most of my time at MIT, they have been very supportive and they always kept faith in my success. You have all been very kind with me, even when the atmosphere was tensed. Special thanks to my mom which made the end of this Ph. D. more comfortable, and to Heather, which had to share her boyfriend with a thesis. Heather was also an important part of this thesis by making sure that the text flows better than what a 5-year-english-immersion-at-MIT can do, with all these french speaking people around. Comment pourrais-je oublier le support moral de ces CANUCKS: Alain, Daniel, Robin, Luc, Marie-Josée, Michèle, Sylvain, et atures, qui ont su mettre un peu de couleur québécoise dans ce milieu multi-culturel.

This thesis really belongs though, to all the subjects that participated in the study. They are the only ones who know how patient they have been. Thank you very much.

Finally, I am afraid that this study might be the end of an era: the Wrist Rocket era! I need to say a special thank to this device which has been the object of several hours of study and concerns, by several people in the Newman Laboratory...
I came to MIT to become a knowledgeable man; what I found was wisdom and faith.
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Chapter 1

Introduction

The goal of this research was to understand how humans control hand-held power tools. Better understanding of human performance in this context may be helpful for the automation of industrial processes to improve productivity or to replace human operators in potentially dangerous work situations. Furthermore, it may form the basis for more precise hand-held tool design guidelines to reduce the prevalence of occupational disorders such as Carpal Tunnel Syndrome (CTS) and Hand-Arm Vibration Syndrome (HAVS). Despite the importance of improving our understanding of human performance in tool usage, we found very few quantitative works on the subject. Current knowledge of human motor control was mainly acquired from unconstrained motion or simple interactive tasks, and hence does not provide a clear picture of the control strategy that tool operators might use. The elucidation of the control strategy can be accomplished by addressing the following three questions:

1. What does the operator do with the tool? i.e. what task is performed?
2. How does the operator accomplish the task?
3. What information he/she uses to perform the task?

Since the control strategy might vary depending on the type of tool being used, we decided to address the above mentioned questions with respect to a hand-held power drill. A drill was selected as the initial power tool for study for the following reasons:

1. it requires gross hand motor behavior (no finger dexterity) once it is positioned on the working piece;
2. it is a quasi-static task, i.e. very little dynamics is involved;
3. operation of a drill is commonly performed with one hand in industry,
4. drilling is a relatively safe task,
5. subjects experienced with operating a drill are easy to find, and finally,
6. it is a task with features common to many other power tools: the user operates the drill via a handle, significant forces are required to conduct the task, and in normal operation, the tool is inherently unstable, making the user responsible for maintaining stability.

Because of time constraints, this present research was limited to the first two questions mentioned above. The particular information that a drill operator might use is an interesting topic but it would add a significant workload and it may not be necessary to understand the mechanics of the task. The first question i.e. "what task is to be performed", was investigated by analyzing a theoretical mechanical model of the static instability induced by applying an axial force to a drill handle. An important conclusion of the analysis is that a minimum hand stiffness is required to maintain the drill stable. The second question was investigated by measuring the upper limb posture of drill operators. Posture influences several mechanical characteristics of the upper limb such as force production capacities, impedance (such as stiffness, viscosity and inertia) and motion or force sensitivity. By observing patterns or invariances in posture under different drilling conditions, we hoped to find distinctive characteristics of the control architecture. The different drilling task conditions studied were: level of axial force exerted on the drill, length of the drill, and drilling location. Various drilling locations were studied for two reasons: firstly, to test whether drill operators keep similar upper limb postures for mechanically similar drilling conditions, and secondly, to identify invariant mechanical aspects of the upper limb posture, by forcing postural variations.

The second question, "how does the operator accomplish the task", was also investigated by studying the particular hand impedance that drill operators use. The hand stiffness was the only impedance characteristic investigated in the research because (1) the experimental apparatus was not suitable to measure viscosity and inertia, and (2) the static instability model previously mentioned only prescribed a minimum bound on the stiffness, and no restrictions on viscosity and inertia. We were interested in the stiffness of the operator's hand because although the theoretical model prescribed a minimum stiffness, subjects had freedom to select a higher hand stiffness. The hand stiffness of subjects was measured while they were pushing on a pivoting stick, a configuration that appears
mechanically similar to the drilling task (Cf. Section 5.2.1). Hand stiffness was measured for various experimental conditions: different axial force levels exerted on the stick, different stick length and other conditions that will be described in Chapter 6. Force level and stick length were chosen because together, they determine the level of static instability of the drill.

This extensive investigation on drill operation is summarized in seven chapters:

CHAPTER 1  INTRODUCTION
The rest of Chapter 1 will describe the importance of hand impedance and upper limb posture in a drilling task, based on current knowledge in human motor control. This discussion will lead to the definition of the research hypotheses. A substantial literature review on the Hand-Arm Vibration Syndrome (HAVS) will complete the chapter. This review was performed because it was the initial motivation for this research.

CHAPTER 2  MECHANICAL ANALYSIS OF STATIC INSTABILITY
A mechanical model of axial force exertion on a drill/stick will be developed in this chapter, in order to better understand the mechanical issues involved and also, to determine if we can predict the action of the operator for variations in axial force and drill length.

CHAPTER 3  UPPER LIMB ANATOMY, JOINT ANGLES, MUSCLE PHYSIOLOGY, AND FORCE EXERTION
Since the research dealt extensively with the biomechanics of the upper limb, this chapter will provide a survey of the anatomy of the upper limb and the difficulties encountered in measuring joint angles. A brief discussion on muscle physiology will follow to explain the importance of limb posture on sensitivity and hand apparent impedance. Finally, we will determine the factors that limit the magnitude of axial force that a subject can produce on a drill handle, under normal conditions.

CHAPTER 4  SELECTION OF UPPER LIMB POSTURE BASED ON MECHANICAL CRITERIA
Drill operators could choose any number of upper limb postures to accomplish a drilling task. He/she may choose his/her posture, not to achieve some particular hand impedance characteristics, but to fulfill some mechanical criteria such as torque minimization at the joints. Two criteria, minimization of joint torques and maximization of
manipulability, will be examined in this chapter along with resulting implications for operator behavior.

CHAPTER 5 STUDY OF UPPER LIMB POSTURE IN A DRILLING TASK

This chapter will describe the drilling task experiments that were performed to study the variation of upper limb posture with drilling location, different magnitudes of axial force exerted and different drill lengths.

CHAPTER 6 MEASUREMENT OF HAND-STICK NODE STIFFNESS FOR A PUSH-ON-A-STICK TASK

This chapter will describe the push-on-a-stick experiment which was designed to study the variation of hand stiffness with changes in stick length, and in axial force level exerted by a subject.

CHAPTER 7 CONCLUSIONS

This chapter will describe how the results of this research can be applied to the design of tools. The various contributions of the research will also be stated and suggestions for future studies given.

1.1 REFINING THE RESEARCH GOALS

Drilling is similar to walking in some ways: most of us can perform the task, with more or less grace, depending on our prior experience and capacities. It "feels" natural, and therefore it appears easy to walk. But if we take a closer look with the eyes of an engineer, walking becomes less simple: walking is in fact so complex that dozens of research laboratories have studied it for several decades. Drilling is also a task that appears simple but requires complex motor coordination. To control a drill means that at least 34 muscles of the upper limb, distributed over at least seven degrees of freedom, must be controlled in real-time by a slow neural architecture with significant time delays (the fastest spinal reflex loops are about 20 to 30 msec). If we add the apparently complex mechanics of the muscles and the multiple degrees of freedom of the rest of the body, we are left with a very complex mechanical system which has as yet no equivalent in robotics. Aware of these difficulties, the engineer would probably have a difficult time explaining the human physiology and mechanics involved in the operation of a drill.
Drilling is a multivariable task performed by a complex "manipulator", the role of the operator is not even well defined. For example, drilling includes some safety issues, and we do not know how important these issues are for the selection of a control strategy. Is the operator more concerned with a good alignment of the drill, suggesting a position control strategy, or a constant force exertion on the drill, suggesting instead a force control strategy? The answer is probably a mix of many possible "goals". Measurements of what drill operators do is also not trivial. The difficulty in studying human performance is the lack of information concerning the inputs to the control system; up to now we have had only limited access to the outputs. It is however possible to get some idea of the control system structure by investigating patterns or invariances in the output "signals", i.e. human reactions to alterations in task conditions. Using this experimental approach, Morasso (1981) studied point-to-point motion of the upper limb. By varying fundamental experimental conditions, he observed very distinctive features which eventually lead to the minimum-jerk model (Hogan et al., 1987).

In this research, the experimental conditions that were varied were the level of axial force exerted on the drill handle and the drill length. Those variables were chosen because they both affect the level of static instability induced by the axial force exerted on the drill handle. As shown in Figure 1.1, if the drill axis is not aligned perpendicularly to the drilling surface, the axial force will induce a destabilizing moment which must be compensated for by the operator. Since we believed that the main role of the drill operator is to compensate for this instability, we expected that by varying the level of static instability, we could observe patterns or invariances in the behavior of subjects. Analysis of extreme cases helps to understand why static instability may influence the strategy of drill operators. Let's assume that a subject was asked to exert an axial force $F$ on a handle under different situations, as illustrated in Figure 1.2. In situation (a) the handle is rigidly fixed on a vertical board, in situation (b) the handle is attached to the board through a spherical joint, and in situation (c) the handle is connected to a wall behind the subject. Intuitively we expect that the subject would behave "differently" in each situation, possibly because the stability characteristics of the handle vary substantially from one situation to another. The particular "behaviors" of interest in this research were the hand driving point mechanical impedance and the upper limb posture that drill operators chose. These variables were selected because of their importance for control of interaction.
FIGURE 1.1 Destabilizing moment induced by the exertion of an axial force on a drill handle: top view.

FIGURE 1.2 Subject exerting axial force on handles with different stability characteristics.
In fact, hand impedance may be used to compensate for the static instability. The compensation can be achieved by appropriate modulation of the hand apparent stiffness. Stiffness may be modulated by simultaneous activation of opposing muscle groups. Hand stiffness (and, in general, mechanical impedance) is also a strong function of upper limb posture. Subjects may therefore select a posture based on the particular stiffness required to stabilize the drill. Posture also influences several mechanical characteristics of the upper limb; for instance, arm posture defines the mapping between end point force and joint torques, and a subject might select a posture that minimizes the torques at the upper limb joints.

Upper limb posture was also investigated for different drilling locations so that we could (1) assess the repeatability of posture for a particular drilling condition, and (2) study the existence of a regularization criteria which would direct subjects in choosing a particular posture. Many other experimental variables could have been studied such as the mass of the drill, the angle of the handle, the direction of drilling, the mechanical properties of the working piece, the level of instability of the spinning drill, the grip force and/or the handle compliance. Analysis of the impact of varying the axial force and drill length was however the most appealing, because we believed that the main role of the drill operator is to compensate for the static instability. In the following sections, the importance of hand impedance and upper limb posture in a drilling task will be discussed.

1.1.1 Hand mechanical impedance in the drilling task

The mechanical impedance of a dynamic system, defined at a specific port of the system (the hand in this case), is the physical characteristic of the system which determines the effort variable at this particular port (the reacting force), in response to an imposed flow (displacement and its derivatives), at this same port. For instance, the commonly referred to "stiffness of a manipulator" is only the static characteristic of the port impedance. The hand mechanical impedance is of particular interest in tool operation because it has been suggested that humans take advantage of their hand impedance to provide stability when performing a contact task. Muscles have intrinsic mechanical properties, thus humans may not need to rely on their reflex control loops to interact stably: the fastest reflex loop that exists is in the order of 20 msec, a time delay which is sufficient to impede the stability of the system for rapid control tasks (Hogan, 1985). It has been shown that humans have the potential to modulate their limb impedance, through coactivation of the antagonist joint muscles (Murray, 1988) or by changes in limb posture.
(Mussa-Ivaldi et al., 1985). However, it appears that the orientation of the stiffness field at the hand, for a fixed arm posture, can not be voluntarily modulated. In addition, it has not yet been proven that humans voluntarily tune their limb impedance for a particular task. It could be that hand impedance is a side effect of muscle activation. A recent study by Lacquaniti et al. (1993), however, showed very distinctive and "mechanically sensible" modulation of hand impedance in the course of catching a ball. Both stiffness and viscosity increased just before impact, and viscous resistance was predominantly aligned with the ball trajectory.

The ability to voluntarily change one's hand mechanical impedance could be very useful for a drilling task. Mechanical models of static instability while pushing on a pivoting stick (see Chapter 2) show that the drill operator hand mechanical stiffness magnitude, in the direction perpendicular to the drill axis, must vary with the level of static instability. Thus humans could tune their hand stiffness to offset drill instability. In a sense, "impedance modulation" could be considered as a control strategy.

Thus far, researchers in motor control have concentrated on understanding how humans perform free unconstrained motion tasks. Very few studies have been done for interaction tasks. A book recently published by Winters and Woo (1990) on "Multiple Muscle Systems" contains very little information on contact tasks, compared to the large amount of data for unconstrained studies. Hence, upper limb mechanical impedance was mainly studied during unconstrained tasks and, typically, only in a horizontal plane. Results showed, for instance, that the apparent stiffness at the hand has an ellipsoid shape with a main axis almost directed toward the shoulder (Mussa-Ivaldi et al., 1985). The magnitudes of stiffness measured were in the order of 200 to 400 N/m. Some of the ellipsoids experimentally measured are shown in Figure 1.3. One-joint and two-joint studies were done with interacting force fields that induced instability, but it is not clear how the results are to be extrapolated to a more realistic task such as drill operation, since subjects could in fact use the geometric constraints to help in performing the task. Finally, no data exists on upper limb impedance perpendicular to the plane formed by the arm and the forearm.
FIGURE 1.3 Stiffness ellipses obtained from four subjects during a postural task with the upper limb maintained in the horizontal plane (Mussa-Ivaldi et al., 1985).

FIGURE 1.4 Planar two link model of the upper limb.
1.1.2 Upper limb posture in the drilling task

Drilling is in fact a complex motor coordination task that requires synergistic control of several muscles and articulations of the human body. For instance, drilling uniquely specifies three degrees of freedom (X,Y,Z of the drill bit), and at the same time restricts the range of the three other rotation degrees of freedom of the drill. If we consider the upper limb only, the human arm has (at least) ten degrees of freedom available to perform the task. An example of such an excess degree of freedom is clearly observed in a planar two link manipulator, as shown in Figure 1.4. If the task is to locate an endpoint in both the X and Y directions, there are an infinite number of possible manipulator configurations to perform the task, simply by altering the distance \( R \) between the endpoint and the shoulder. This analogy to a planar manipulator can be extended to a 3D manipulator such as the human arm for drill operation; the manipulator now has at least ten degrees of freedom available to perform a six degrees of freedom task. The operator can select from an infinity of arm configurations, while still respecting the physiological limits of his/her limb joints. Either humans select completely random configurations while drilling or, for instance, they could take advantage of kinematic redundancy to fulfill some regularization criteria such minimizing upper limb joint torques. From a biomechanical point of view, there are many criteria that may account for a particular posture selection. Only three were studied:

1. minimization of joint torques;
2. maximization of manipulability;
3. isotropy condition.

These criteria will be discussed in Chapter 4.

A preliminary experiment was conducted in order to get some idea of the particular arm posture selected by subjects, and to determine whether there were some patterns or invariances. Twenty-three subjects were asked to drill 10 holes on a vertically oriented wood panel. The only two restrictions given were that subjects had to hold the drill with only one hand, while the other hand could not be used to grab any surrounding structures. This drilling method is not necessarily one normally chosen by all drill operators, but it is one which is commonly used in industry (personal visits to industrial sites). After drilling one hole, some of the subjects were told to walk away from the board by at least three meters. The only data acquired from these experiments were video tapes of subjects performing the task, the main anthropometric measurements of subjects, and the height of the holes that the subjects made on the board.
Analysis of the video tapes showed that subjects seemed to have repeatable postures when drilling at the same height. The posture was also similar from one subject to another. This suggests that the choice of arm posture is not random and that some criteria could exist to dictate the appropriate arm configuration for drill operation. Analysis of the height of the holes in relation to anthropometric measurements was performed to find out if any clear relationship existed; for instance, subjects might have drilled the holes at the shoulder height. Results (Cf. Figure 1.5) show that most of the time, the drilling location was restricted between the elbow and the shoulder, but no clear relationship could be drawn with any of the anthropometric measurements i.e. the subject height, the shoulder height, the drilling height and the elbow height. This information was used to restrict the range within which subjects would be asked to drill in our experiments.

FIGURE 1.5 Comparison of different drilling heights for 23 subjects; means are indicated by the "o" symbol, and vertical bars are the range of drilling heights chosen by a subject.
1.2 DEFINING RESEARCH HYPOTHESES

In order to provide a precise direction to the research, three hypotheses were established:

HYPOTHESIS 1: *Drill operators select a repeatable upper limb posture for similar mechanical drilling conditions.*

If drill operators use a given regularization criteria, such as minimization of joint torques, one should expect that the upper limb posture is repeatable for similar mechanical drilling conditions. This hypothesis was tested by measuring the upper limb postures of subjects that were asked to drill at different locations with different axial force levels and different drill bit lengths. Using these data, several questions were also addressed:

1. Does posture vary across subjects?
2. Does posture vary with drilling height?
3. Does posture vary with the level of axial force exerted on the drill?
4. Does posture vary with drill length?
5. Is there evidence of a regularization criterion underlying the choice of posture?

HYPOTHESIS 2: *The control strategy used in drilling operation is equivalent to that used in pushing on a pivoting stick.*

Since we believed that the main role of the operator was to compensate for the static instability of the drill, we expected that the control strategy used in drilling operation is equivalent to that used in pushing on a pivoting stick. This hypothesis was tested by comparing upper limb posture for when the drill was off as well as on.

HYPOTHESIS 3: *In hand-held power drill operation, static instability influences the subject hand driving point mechanical impedance.*

Since static instability models developed in Chapter 2 indicate that the operator's hand must have a particular stiffness shape and magnitude, when exerting an axial force on a drill, we expected that in hand-held power drill operation, static instability may influence the subject hand driving point mechanical impedance. This was tested by measuring the static impedance of subjects that were asked to push on a drill handle mounted on a pivoring stick. This special setup allowed us to isolate the static instability phenomenon.
from other variables of the drilling task. The measurements were made for different levels of static instability by changing the stick length and the axial force exerted on the stick.

1.3 HAVS: THE ORIGINAL MOTIVATION FOR THIS RESEARCH

The initial direction for this research was to investigate the role of the hand mechanical impedance in the Hand-Arm Vibration Syndrome (HAVS). This syndrome is proven to be prevalent in people exposed to vibrations of hand-held power tools. Although a drill is not considered a particularly "dangerous" hand-held tool, our research on HAVS has focused on it because drilling conditions are easier to control. For instance, we did attempt some preliminary work with a palm sander, where several problems were encountered:

1. the grasping technique significantly changed from one trial to another,
2. the interactive force between the sander and the "environment" depended on the direction and speed of motion of the sander;
3. the measurement of interaction forces between the sander and the panel was difficult to achieve due to low tangential forces in conjunction with high normal forces.

Since a drill has several features in common with more "dangerous" power tools, the investigation of drill operation can nevertheless provide useful information to help clarify HAVS. Several countries (USA, Canada, Italy, Finland etc.) have studied the subject affliction, but despite many years of research the cause is not yet well understood. The following provides a 1992 literature review of Hand-Arm Vibration Syndrome studies and a summary of the results to date. This information can be very helpful in understanding the importance of studying human performance in the operation of hand-held power tools.

1.3.1 The hand-arm vibration syndrome (HAVS)

At the beginning of the century, researchers discovered that workers using vibrating powered tools showed symptoms similar to those of Primary Raynaud's Disease (Wasserman, 1987). Raynaud's disease was first described in 1862; it was also called White Finger Syndrome as patients suffering from this disease saw their fingers suddenly becoming white and cold. Attacks typically struck both hands where patients tended to lose skin sensitivity at the fingers. Raynaud's disease was determined to be the...
consequence of vascular spasms of the small arteries of the hand. These spasms reduced blood flow to the hands, and with time, led to ischemia (Taylor, 1974). The etiology of these spasms was believed to be purely a metabolic reaction.

Raynaud's disease afflicted 5% to 8% of the population, 90% of whom were female. However, in 1918, epidemiological studies (Wasserman, 1987) discovered that White Finger Disease symptoms were prevalent in a working population exposed to vibration powered tools, and that these symptoms were highly spread out amongst workers who, moreover, were males. Since the cause was external to the body, the related pathologies were classified as a syndrome named Raynaud's Phenomenon of Occupational Origin. Other terms presently used are: Hand-Arm Vibration Syndrome (HAVS) or Traumatic Vasospastic Disease (TVD).

Recent studies have shown that workers suffer many more symptoms than those identified in the early 1900's. These symptoms are summarized in Table 1.1 below.

| Vascular          | • Blanching of all fingers, but not thumbs
|                   | • Blood vessel wall thickening
|                   | • Blood viscosity increases
| Neurological      | • Decrease in motor and sensory nerve conduction velocities (from finger to wrist)
|                   | • Numbness, tingling
|                   | • Loss of light touch
|                   | • Pain and temperature sensation
| Muscular          | • Atrophy of muscles
|                   | • Muscle force decreases (grip strength)
|                   | • Pronounced EMG changes
| Others            | • Bone cysts
|                   | • Joint degeneration
|                   | • Fatigue, vertigo, headache, insomnia, anxiety, instability

**TABLE 1.1** Symptoms presently associated with HAVS (NIOSH, 1989)

It appears that these symptoms are degenerative changes associated with muscular, skeletal, neurological and vascular systems.

HAVS develops through four distinct stages (see Table 1.2) and can have a latency period of up to 14 years (Brammer et al., 1981). Up to the end of the second stage, the
syndrome is thought to be reversible. In the following example, Brammer et al. (1981) describes in detail the progression of stages in blanching of the fingers, one of the most harmful consequences of vibrating tools (Table 1.2):

<table>
<thead>
<tr>
<th>Classification</th>
<th>Signs and symptoms</th>
</tr>
</thead>
</table>
| Stage 1        | • Episodic blanching of distal phalanges  
                 | • Borderline decrease in motor and sensory conduction velocities  
                 | • Minimal changes in hand radiographs  
                 | • Periodic numbness and pain in fingers  
                 | • Paresthesia may be present |
| Stage 2        | • Extended episodic blanching  
                 | • Further decrease in motor and sensory conduction velocities  
                 | • Slight EMG abnormalities  
                 | • Moderate changes in hand and arm radiographs  
                 | • Pain and numbness lasting longer at rest and at night  
                 | • More pronounced hyperesthesia |
| Stage 3        | • Blanching extended to all fingers but not the thumbs  
                 | • Greater decreases in motor and sensory conduction velocities  
                 | • Pronounced EMG changes  
                 | • Pronounced changes in hand and arm radiographs  
                 | • Some restriction of hand and arm movement  
                 | • Atrophy of hand/arm muscles  
                 | • Exaggerated subjective symptoms |
| Stage 4        | • Frequent blanching of all fingers but not the thumbs  
                 | • Pronounced decrease in motor and sensory nerve conduction velocities  
                 | • Very pronounced EMG changes  
                 | • Pronounced changes in radiograph  
                 | • Increased motility restriction and muscle atrophy  
                 | • Further exaggerated subjective symptoms |

**TABLE 1.2** The four Stages of HAVS Symptoms (NIOSH, 1989).
"When the hands are first exposed to vibration, a person will usually report tingling followed by numbness of his fingers. After regular, prolonged exposure, the fingers feel swollen, painful and inflexible, these symptoms subsiding during a weekend break from work. With further exposure (usually measured in years), the blanching of a fingertip occurs, usually in winter. This episodic blanching of fingertips, generally precipitated by cold, is often not associated with the use of vibrating tools. The time interval between the first exposure to vibration and the appearance of a white fingertip is known as the latent interval, and is related to the amplitude or level of vibration entering the hand. The shorter the latent interval, the more rapid is the rate of progression of disorders. With continuing vibration exposure, the blanching occurring during an attack extends from the fingertip to the base of the finger. Further exposure leads to the involvement of other fingers, principally those in contact with the most intense vibration. At this stage, the affected areas are often asymmetrically distributed on the hands. Ultimately, three of four digits bilaterally are involved, the thumb being the last to be affected."

Since the 1960's, many studies have tried to explore the problem from various directions. Some groups were concerned with finding the etiology of the syndrome, and with creating reliable testing procedures to diagnose the various symptoms of HAVS. Many tried to design instrumentation devices to describe the vibration characteristics of the powered tools. Others performed epidemiological research to investigate the degree of HAVS occurrence for different power tools. Finally, experiments have been conducted to determine the actual transmission of vibrations to the arm. The current state of research in each of these areas will be reviewed in the following sections.

1.3.2 Etiology of Syndrome

HAVS is a multisymptomatic disease; therefore it is believed that different symptoms have different etiology. The blanching fingers, as in Raynaud's disease, is a result of reduced blood flow in the hand following a vasospasm of the arteries of the hand. There is some evidence that vasoconstriction of the blood vessels is a response to vibration. Vibrations excite the Pacinian corpuscles which produce reactions in the vasculature via a reflex linkage through the sympathetic nervous system (Pyykkö et al., 1981). Regular activation of this reflex loop could explain the hypertrophy of the muscular layer of the vessel walls, which in turn, reduces the lumen. However, even after surgery, which eliminates the sympathetic action on the vessels, the vasospasms reappear after a 6 to 8 week period. Therefore, it does not seem possible that the central nervous system is a dominant factor in vasoconstriction; other factors must exist to locally control the vessel constriction. In fact in 1977, Lancet discovered prostaglandins thombaxane
A2, and prostacyclin which are respectively a vasoconstrictor and a vasodilator present in the blood (Brammer et al., 1981). It is thought by some that the presence of vibration produces an accumulation of these vasoactive substances. Others think that the vessel muscular layers become very sensitive to noradrenaline under a vibration stimulus, thus favoring vasoconstriction (Azuma et al., 1981). In summary, Pykko et al. (1981) explains that vibration produces a stress situation in the central nervous system by stimulating the pacinian corpuscles and by transmitting vibration throughout the body. The body thus responds to this stress by activating certain mechanisms which produce vasoconstriction in both hands, including the contralateral hand which is not exposed to any vibration stimulus (Brammer et al., 1981; Pykko et al., 1981).

Neurological changes call for a different mechanism than vasoconstriction. One theory proposes that the vibration entering the hand causes degeneration of the pacinian corpuscles (Brammer et al., 1981) which are sensitive in the range 60 to 700 Hz (Kandel et al., 1991). This degeneration could explain the numbness, tingling, paresthesia, pain and temperature sensations. Nevertheless, it is not clear what mechanism leads to a decrease in motor and sensory nerve conduction velocities in the area between the finger and the wrist. Carpal tunnel syndrome (CTS) could provide an explanation for these neural changes, however CTS does not lead to a reduction of conduction velocities. Two mechanisms are suggested by Juntunen (1987): (1) it is a Wallerian degeneration due to direct mechanical trauma to the nerve caused by the vibration, or (2) it is a segmental demyelination, through ischemic damage to the nerve, from vasospasms. Most recent studies (Taylor, 1974) suggest that vascular and neural components develop independently.

1.3.3 Diagnostic Tests

There are no diagnostic techniques to tell accurately how much a patient is affected by HAVS. This is because HAVS has a variable latency period and furthermore other diseases can produce pathologies similar to the HAVS symptoms. Most diagnostic techniques monitor only one symptom. Some of these tests are presented in Table 1.3. In order to validate these tests, correlation studies were performed with the HAVS history of the workers. Despite these efforts, no safety standards can yet reliably quantify the susceptibility of a worker to contract HAVS based on the knowledge of his exposure to vibration.
<table>
<thead>
<tr>
<th>Diagnostic test</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Provocation test CPT</td>
<td>Short exposure: Patient immerses his hand and wrist in icy water for 1-3 minutes. Before, during, and after the test, the blood flow in the fingers is recorded. Long exposure: Patient immerses his hand and wrist in 100(^\circ)-150(^\circ) water for 10-15 minutes. When his hand is removed from the water, the time is measured for the finger to regain its color.</td>
</tr>
<tr>
<td>Plethysmography</td>
<td>Technique to measure blood flow by monitoring the volume change of the fingers that occurs at each heart pulsation. Usually used in conjunction with the CPT.</td>
</tr>
<tr>
<td>Aesthesiometry</td>
<td>Two-point and depth discrimination of the finger tip. Used to check peripheral neural changes.</td>
</tr>
<tr>
<td>Arteriography</td>
<td>Biopsy of finger arteries to observe physiological changes.</td>
</tr>
<tr>
<td>Grip force test</td>
<td>Determines maximum grip force and fatigue curves under various conditions.</td>
</tr>
<tr>
<td>Nerve Conduction test</td>
<td>Monitors median and ulnar nerves by applying an electrical stimulation of the nerves at a certain point, then records the time for a motor response to occur.</td>
</tr>
<tr>
<td>Sensory acuity test</td>
<td>Includes various sensitivity tests: (1) cotton wool test (for light touch), (2) hot and cold probes (for temperature), (3) pin prick (pain), (4) tuning fork (vibrotactile). Any abnormal response can indicate a neural change [322].</td>
</tr>
</tbody>
</table>

**TABLE 1.3** Common diagnostic tests for HAVS (NIOSH, 1989).

### 1.3.4 Vibration Characteristics of power tools

The measurement of tool vibrations presents several difficulties. Typically, accelerometers are placed on the handles of the tools, and the subject is asked to grasp the handle and perform the task. Depending of the position of the hand and the technique used to execute the task, the recorded accelerations will differ. The accelerometer dynamics, and particularly the method used to fix it to the handle, introduce important artifacts which should be taken into account. Most data processing and experimental systems can not pick up high acceleration peaks which are important in many tools (Starck, 1984). Furthermore, different techniques are used to compute the power spectrum. Aware of these limitations, we are ready to consider the results of various studies (Reynolds *et al.*, 1984a; Taylor, 1974; Suggs *et al.*, 1981; Miwa, 1981; Auerbach, 1981) that determined the acceleration spectrum of different vibrating power tools in industry (chisel, grinder, drill, chain saw, circular saw, rivetter, chipping hammer). Most of these vibrating tools exhibit a frequency spectrum with substantial energy from 30 Hz...
to 2000 Hz, with a maximum energy range that varies from one tool to the other, but is usually under 1000 Hz.

1.3.5 Epidemiological studies

Epidemiological studies have been conducted in different industrial applications to identify the symptoms associated with workers using vibrating tools. NIOSH (1989) has compiled most of the important studies into one document. One should refer to this document for further information. Most of the knowledge obtained from these studies is described in the Etiology section of this chapter. It is important to remember that this knowledge is limited by the quality of the diagnostic tests described previously. Many correlation studies were performed to determine which parameters of the environment-tool-human complex control the susceptibility of a worker to contract HAVS. No clear relationship were established since it is difficult to describe the exposure characteristics of a worker to vibration. However, based on field experience, certain parameters are thought to be important. They are listed in Table 1.4.

1.3.6 Vibration transmission to the arm

To get a better understanding of how vibrations affect the arm, several studies have been conducted describing the transmission of vibration to the arm. In a study by Reynolds et al. (1977a), accelerometers were fixed to the skin at different locations on the upper limb, from the hand to the shoulder. Subjects were asked to hold a vibrating handle with a prescribed grip force. By comparing the frequency response at each location, the author was able to come up with some conclusions. An important conclusion of the study stated that for an input vibrating force of 100-150 Hz at the hand, the detectable acceleration signals were restricted to the hand. Over 150 Hz, they were localized at the fingers. However, at 10 Hz, substantial vibration was present up to the shoulder. The validity of some of his detailed analysis is questionable since the accelerometer fixation technique adds dynamics to the measurements. Similar results were obtained by Reynolds (Reynolds et al., 1984a; Reynolds et al., 1977b). Again subjects were asked to maintain a grip force on a vibrating handle. The interaction force and handle displacement were measured to obtain the driving point impedance frequency characteristics. By fitting third and fourth order models to the frequency curves, the author was able to show again that at high frequencies (> 100 Hz) most of the vibration was localized at the hand.
<table>
<thead>
<tr>
<th>Factor categories</th>
<th>Modifying factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>• Dominant vibration amplitudes entering the hand&lt;br&gt;• Dominant vibration axis relative to the hand&lt;br&gt;• Years of employment involving vibration exposure&lt;br&gt;• Total duration of exposure each workday&lt;br&gt;• Pattern of work/rest exposure each workday&lt;br&gt;• Nonoccupational exposure to vibration</td>
</tr>
<tr>
<td>Biodynamic</td>
<td>• Hand grip forces (compressive and push or pull forces)&lt;br&gt;• Surface area, location, and mass of parts of the hand in contact with the source of vibration&lt;br&gt;• Posture (position of the hand and arm relative to the body)&lt;br&gt;• Other factors influencing the coupling of the vibration source to the hand (e.g., texture of handle - soft, complaint vs. rigid material)&lt;br&gt;• Mechanical impedance of the upper limb</td>
</tr>
<tr>
<td>Individual</td>
<td>• Factors influencing source, intensity, and exposure duration (e.g., state of tool maintenance, operator control of tool, work rate, skill, and productivity)&lt;br&gt;• Biological susceptibility to vibration&lt;br&gt;• Vasconstrictive agents affecting the peripheral circulation (e.g., tobacco, drugs, etc.)&lt;br&gt;• Predisposing disease or prior injury to the fingers or hands (e.g., trauma, lacerations, diabetes, connective tissue disorders)</td>
</tr>
</tbody>
</table>

**TABLE 1.4** Categories of factors that may modify the biologic effects of hand-arm vibration exposure (Brammer et al., 1981).

For a similar experimental set up using real tools (Reynolds et al., 1984b), power levels transferred to the hand were estimated. It was found that there was substantial energy from 6.0 Hz to 1000 Hz and that the maximum power level was at low frequencies, usually at the main frequency mode of operation of each tool. A crude estimate of power entering the hand ranged from $6.5 \times 10^{-3}$ J/s for a pneumatic grinder to $7 \times 10^{-3}$ J/s for a chisel. In an experiment by Griffin et al. (1981), subjects were asked to hold a vibrating handle. The apparent mass of the arm at the handle was estimated by the ratio of force (contact force) to acceleration. Results showed a variability dependent upon vibration level, grip force, arm angle and subject. The authors also showed that special material can be used to alter the vibration transmitted to the hand for frequencies greater than 100 Hz; however, it also amplified vibrations at lower frequencies.

Other studies attempted to design damping systems to alter vibration (Miwa, 1981, Auerbach et al., 1981, Rodgers et al., 1981, Suggs et al., 1981). Resilient material on the handles reduced transmission at frequencies over 200 Hz but it showed poor results at lower frequencies. Therefore, vibration damping systems should be part of the tool-handle interface, such as designed by Rodgers (1981) or Miwa (1981), if we want to alter frequencies over a larger range.
1.3.7 Analysis and Conclusions

The previous sections have summarized current knowledge of HAVS. The syndrome is characterized by an extensive list of proposed symptoms, with a distinct lack of understanding of the physiological mechanisms underlying these symptoms. The symptoms encountered vary a great deal from one subject to another, an observation which supports the need for further correlation studies with vibration exposure. Such studies are hardly reliable due to the large number of parameters to be controlled (Cf. Table 1.4), nevertheless, many different groups are attempting to establish standards based on field experiences.

Ergonomical factors alone (c.f. Table 1.4) cannot sufficiently define a dose-response relationship. More generic variables must be proposed. For instance, from a biomechanical point of view, vibrations (of any frequency) entering the arm produce mechanical stresses in the body tissues. The tissues, subjected to cyclic stresses, absorb energy because of their hysteretic behavior. This situation can lead to fatigue of the tissue which will undergo structural modifications with time. Such a degenerative process could explain the physiological problems of HAVS. Most of the factors listed in Table 1.4 are related to stress and energy absorption levels, two variables that occur at any frequency of vibration. This could explain the broad occurrence of HAVS in industry where the mechanical fatigue of tissues provides a plausible explanation for the effect of cumulative exposure. Furthermore, obvious symptoms of HAVS (vasospasms, reduction of grip force) occur at the hand where vibrations are localized at higher frequencies (Reynolds et al., 1977a).

It is the realm of physiology to explain how stress and energy absorption can produce the physiological symptoms encountered in HAVS. At the moment, there are no studies that can provide such information. It is still a postulate that stress and energy absorption adequately determine the risk of acquiring HAVS (i.e. to define a dose-response relationship). If this postulate is valid, a preventive solution to HAVS would be to maintain stress and energy absorption at the lowest possible levels. Such a solution is achieved by reducing the amplitude of the vibrations entering the upper limb over the whole range of frequencies.

The vibration amplitude transmitted from the tool to the hand depends upon several factors:

- the mechanical characteristics of the hand-tool interface (the port impedance),
• the type of tool (as well as its state of maintenance);
• the required task.

Typically, the tool and the task are given, while the mechanical characteristics of the hand-tool interface depend directly on the impedance of the upper limb seen by the tool handle. The impedance provides mechanical support to the tool in order to ensure its stability, control its motion, and tune the interacting force pattern at the tool-environment interface. Forcing changes in the hand impedance may not be easy. For example, it is known that a lower grip force reduces transmission of vibrations to the hand (Reynolds et al., 1984b). However, if a worker were to reduce his grip force, the tool may become unstable. Assistive mechanical devices could be designed to compensate for a necessary reduction in grip force. Such a situation would necessitate trading-off between the mechanical and physiological requirements of a task.

Further trade-offs must be made in considering the requirements for appropriate control of a tool: proprioceptive information should not be removed and the task should not exceed the upper limb mechanical limitations. Such limitations restrict the mechanical impedance that the upper limb can provide to the tool handle. An appropriate limb impedance can only be determined through an integrated analysis of the mechanical, proprioceptive, physiological and ergonomic aspects of the task.

Measurements of operator upper limb impedance were performed for certain power tools. Such measurements, if accurate, can be useful for correlation studies with workers exposed to vibrations and provide the basis for designing vibration isolating mechanical devices to protect the worker. Several questions will be faced: What should their function be exactly? Which mechanical aspect of the task should they assist (e.g. stabilizing the tool, producing an adequate tool-environment interface force)? How will they affect the proprioception of the worker? Are they compatible with the upper limb capabilities? Are they technically and financially feasible for the given task (design of robots to replace an operator would obviously be an adequate protection)? In order to answer to these questions it is important to learn more about the strategy used to control vibrating powered tools: what are the impedance characteristics at the hand-tool interface? How does the upper limb produce the appropriate impedance? What is the range of flexibility that the upper limb has to produce a specific hand impedance? What are the variables of the task that affect the impedance that the tool operator chooses? Most of these questions will be addressed in this thesis in the context of hand-held power drill operation.
Chapter 2

Mechanical Analysis of Static Instability

This chapter investigates the mechanics of static instability induced by an axial force exerted on a drill handle. In the previous chapter, it was mentioned that drill operators could take advantage of their hand stiffness to offset this instability. Our investigation of static instability will be conducted by assuming that operators do in fact use their hand stiffness to stabilize the hand-drill kinematic chain. In this chapter, we intend to demonstrate the following:

- static instability determines a lower bound of the stiffness magnitude required by the operator;
- an operator can voluntarily select either the hand rotational stiffness or tangential stiffness to stabilize the drill;
- the proportion of rotational stiffness versus tangential stiffness chosen by an operator cannot be predicted from a simple mechanical analysis alone;
- it is not possible to predict, from the same mechanical analysis alone, if a long or a short drill bit is less "demanding" from the operator;
- the level of axial force exerted on the drill handle, the manipulator joint stiffness, the kinematics of the drill, and the manipulator, are all variables which influence the level of static instability inherent in drilling; and finally,
- pulling can be unstable when the pivoting point is located behind the shoulder of the subject.
We arrived at these conclusions by investigating the static instability phenomenon by force balance or energy based analysis, for different types of manipulators:

1. an infinite length manipulator with shoulder stiffness only;
2. a prismatic manipulator with shoulder stiffness only;
3. a general manipulator, and
4. a prismatic manipulator with both shoulder and hand (wrist) stiffness which, at the same time, can be extended to a general manipulator.

2.1 INFINITE LENGTH MANIPULATOR

When an operator exerts an axial force $F$ on a drill, there is a destabilizing moment induced, as shown on Figure 2.1. In order to keep the drill in equilibrium, the operator must provide a compensating moment $M$. This situation is equivalent to pushing on a stick, if we assume that the drill does not induce any other mechanical instability.

Assume then that a manipulator applies a force $F_a$ at the tip of a stick which is mounted to a spherical joint on a surface. If a disturbance $X$ is applied to the stick, due for instance to an error in positioning of the manipulator, a destabilizing moment is induced about the pivoting point $O$, and the manipulator must compensate for this moment to keep the stick stable. The compensating moment produced by the hand on the stick could come, for instance, from a transverse force $F_t$ as shown in Figure 2.2. For an impedance controlled manipulator, this means that the transverse stiffness of the manipulator must be at least equal to $K_t = \frac{F_t}{X}$. Writing a moment balance equation about the point $O$ gives:

$$-F_a X + F_t L \cos \theta = 0$$  \hspace{1cm} (2.1)

$$\Rightarrow F_t = F_a \frac{X}{L \cos \theta}$$  \hspace{1cm} (2.2)

$$= F_a \frac{X}{\sqrt{L^2 - X^2}}$$  \hspace{1cm} (2.3)
FIGURE 2.1 Destabilizing moment induced by axial force applied on drill handle.

\[ M_{\text{destabilizing}} = F_a x \]

FIGURE 2.2 Model of axial force induced instability compensated with a tangential force.
\[ \equiv \frac{I^i}{a} \frac{X}{L} \quad \text{for} \quad X \ll L. \quad (2.4) \]

For a drill, the ratio X/L is in fact small i.e. around 4 cm. Therefore, the minimum transverse stiffness required is:

\[ K_T = \frac{F}{X} = \frac{I^i}{a}. \quad (2.5) \]

We assumed here that the axial force does not change orientation with deviation of the stick; this is equivalent to assuming an infinite length manipulator.

The minimum stiffness clearly depends on the axial force applied to the drill and the length of the drill bit. If the transverse stiffness is plotted versus L, we get the curve shown in Figure 2.3. This curve describes the trend we expect to see in the transverse stiffness of the manipulator. The graph shows that the stiffness changes significantly for a stick length of up to 4 cm, and that it changes more rapidly for shorter sticks. The two vertical lines on the graph mark the range of typical lengths for drills with bits. The stiffness varies by a factor of two within this region. Assuming that the axial force is around 100 N, the stiffness values are within the range of those obtained by Mussa-Ivaldi et al. (1985), taking into account that the task required higher muscle activations compared to his experimental situation, and that muscle stiffness grows with muscle activation level (Weiss et al., 1988; Zahalak et al., 1979; De Serres et al., 1991). When the axial force is directed away from the stick (i.e. a pulling situation), transverse stiffness of the manipulator is not necessary to keep the stick stable: the action of the pulling force itself creates a stabilizing moment about the pivoting point O.

The previous development assumed that the manipulator would balance the destabilizing moment by applying a transverse force at the stick extremity. A subject may also balance the destabilizing moment by applying a moment on the handle using the rotational stiffness of the hand. In order to determine how stiffness varies with stick length, we assume that the manipulator translates with the stick extremity and only the rotational stiffness component of the manipulator comes into play. In this case, the moment required on the handle remains a constant with stick length, if the positioning error of the manipulator is constant, and is given by:
FIGURE 2.3 Transverse linear stiffness variation with stick length, for an infinite length manipulator.

FIGURE 2.4 Drill stabilized with a moment induced by the rotational stiffness of the hand.
where \( M \) is the applied moment, \( F_a \) is the axial force exerted on the stick and \( X \) is the positioning error of the stick extremity, which is estimated to be around 1 cm. Under this condition, the ratio \( X/L \) is small and the required rotational stiffness becomes:

\[
K(l) = \frac{F_a X}{\sin^{-1}(\frac{X}{L})} \approx F_a l, \text{ for } X << L.
\]

When a subject uses a moment compensating technique to stabilize the drill, his rotational stiffness must increase proportionally with axial force and drill length. Conversely, for the transverse force compensating technique, the subject applies less transverse force with increasing drill length. It is not known whether a subject uses a transverse force technique or a moment technique to stabilize the stick. We can expect that drill stabilization may employ a mix of the two strategies, where the importance of each varies with stick length.

## 2.2 THE PRISMATIC MANIPULATOR

The previous discussion of drill stability assumed that upon rotation of the stick, the force produced by the manipulator would keep the same orientation. This is in fact not the case since, in general, the particular geometry and mechanics of the manipulator can affect stability by changing the mapping between joint torques and endpoint force. This can be shown by assuming a prismatic manipulator attached at one extremity to a revolute joint fixed in space and equipped with a linear torsional spring to ensure rotational stiffness. Assume the manipulator is attached to the stick via a spherical joint, free of friction or any inherent impedance in the rotational degree of freedom. The axial force on the stick is produced by the prismatic joint which is under force control. Therefore, under a slight rotation of the stick from the normal, the axial force produced by the manipulator changes orientation as shown in Figure 2.5. Under this new force equilibrium, we can again derive what should be the minimum stiffness at the revolute joint to ensure stability.

Assuming equilibrium of the system after a given rotation of the stick, the manipulator produces two distinct forces on the stick: \( F_a \) and \( F_t \). If we perform a
moment equilibrium about the pivoting point \( O \) of the stick, we can state that stability is ensured if:

\[
F_t d_t \geq F_a d_a ,
\]

where,

\[
d_t = L_s \cos(\theta + \alpha) ,
\]

\[
d_a = L_s \sin(\theta + \alpha) .
\]

\[
L_s \theta = L_m \alpha = \alpha
\]

Given the following relationship

\[
F_t = \frac{K_a \alpha}{L_m} ,
\]

and assuming small deviations, we find that

\[
K_a \geq F_a \frac{L_m^2}{L_s} \tan(\theta + \alpha) \frac{\theta}{\theta}
\]

for a stable condition. Assuming small deviations again, and the following relationship between apparent transverse stiffness of the manipulator and torsional stiffness of the revolute joint

\[
K_t = \frac{K_a}{L_m^2} ,
\]

we finally obtain the condition on transverse stiffness for ensuring stability of the manipulator stick system as:

\[
K_t \geq \frac{F_a}{L_s} \frac{\theta + \alpha}{\theta} .
\]

For a long manipulator, this equation reduces to Eq. 2.5 because the second fraction member on the right of the equation becomes unity. Equation 2.14 can be expressed in terms of the geometry of the system by employing Eq. 2.10:

\[
K_t \geq \frac{F_a}{L_s} \left( 1 + \frac{L_s}{L_m} \right) .
\]
FIGURE 2.5 Prismatic manipulator with shoulder stiffness only, pushing case.  $L_m$: length of manipulator, $L_s$: length of stick; $x$: positioning error of manipulator.
This equation is plotted in Figure 2.6 for different values of manipulator length and stick length. The prismatic model produces results that are very similar in shape to the simplest model previously discussed, but the minimum stiffness required for stability is significantly higher, hence demonstrating the effect of manipulator length on the stability characteristics of the system. The prismatic model is even more important when the stability characteristics are analyzed for a pulling situation. The infinite length model showed that pulling is always stable because the force remain in the same direction with a rotation of the drill. Because the manipulator kinematics are added in the model, the prismatic model shows differently: inherent stability is achieved only when the pivoting point of the stick is between the end point of the manipulator and the shoulder revolute joint. A practical example of instability in a pulling situation occurs when gymnasts practice the ring exercise. To explain the instability phenomenon further in pulling, we will discuss the stability requirements for the system shown in Figure 2.7.

A slight deviation \( \Delta \) of the manipulator induces a change in direction of the axial force \( F_\alpha \). Because of the particular geometry of the stick-manipulator system, the length of the manipulator will slightly increase and the axial force will have a component \( F_I \) perpendicular to the stick axis. In order for the system to be stable, the torsional stiffness of the manipulator \( K_S \) must balance the torque produced by \( F_I \) about the revolute joint. We can then obtain a minimum bound on the stiffness of the manipulator in the following way, again assuming small deviations:

\[
K_S \frac{\alpha}{l_m} = F_I l_m
\]

\[
\Rightarrow K_S = F_I \frac{\alpha}{l_m} \frac{\alpha - \theta}{\alpha}
\]

\[
\Rightarrow K_I = \frac{K_S}{l_m^2} = F_I \left( \frac{1}{l_m} - \frac{1}{l_s} \right)
\]

(2.16)

As previously mentioned, the prismatic model has yielded very different results than the infinite length manipulator model:

- Instability induced depends on manipulator length.
- When the pivoting point is "behind" the shoulder revolute joint, the system becomes unstable and the manipulator must provide some action to stabilize it. The stick looks like a spring with a negative stiffness. The shorter is the manipulator, the higher will be the minimum bound on the tangential stiffness.
FIGURE 2.6 Minimum tangential stiffness of the manipulator for stability (pushing situation). The "infinite" line represents the stiffness that was calculated with the simple model (infinite manipulator length: in this case, the abscissa on the graph represents the stick length and not the ratio to the manipulator length). The other lines are from the sophisticated model with various manipulator lengths: .2, .4, .6, and .8 meter.
FIGURE 2.7 Pulling condition, prismatic manipulator.

FIGURE 2.8 Minimum tangential stiffness of the manipulator for stability (pulling condition). The "infinite" line represents the stiffness that was calculated with the infinite manipulator length model: in this case, the abscissa on the graph represents the stick length and not the ratio to the manipulator length). The other lines represent the sophisticated model for various manipulator lengths: .2, .4, .6, and .8 meters.
• If the pivoting point is located at the shoulder revolute joint, then stick kinematics is not important.
• When the pivoting point is between the end point of the manipulator and the revolute joint, the system is inherently stable. The stick looks like a stabilizing spring.
• For a given stick length, a longer prismatic arm is preferable for decreasing the minimum required stiffness.

Two different models have been discussed. First, the infinite length manipulator model assumed an axial force that continued to act perpendicular to the working surface as the stick rotated. Then the prismatic model removed this restriction. We can go a step further in our modelling by examining a general manipulator. This step will demonstrate how the stability analysis can become complex if the dynamics and kinematics of the manipulator are not well known.

2.3 GENERAL MANIPULATOR

A static instability analysis can be conducted for a general manipulator which has known geometrical properties and joint stiffness, but where there is still no stiffness at the junction with the stick. In general, for any manipulator pushing on a stick, the coupled system will be stable if the resultant force applied on the stick, following a small deviation, is aligned on the correct side of the pivoting point of the stick, so as to produce a counterbalancing moment. The change in axial force magnitude and direction can be analysed by computing the differential force following a differential motion of the coupled point.

On the basis of a derivation by Mussa-Ivaldi and Hogan (1992), the differential force can be expressed as:

$$dl = K_l dX,$$

where $K_l$ is the Cartesian stiffness of the manipulator end point, and $dX$ is the displacement of the stick end point. The above authors derived the Cartesian stiffness of a redundant manipulator as:

$$K_l = [J(k - \Gamma)^{-1}J^T]^{-1},$$

(2.18)
\[ \Gamma_{i,m} = \sum_{m=1}^{M} \frac{\partial^2 X_m}{\partial \theta_i \partial \theta_i} J'_{m}; \tag{2.19} \]

\(J'_{m}\) is the interacting force at the end effector along direction \(m\); \(k\) is the matrix that relates different joint rotations to differential joint torques; \(J\) is the Jacobian of the manipulator for a given configuration; \(\theta_i\) is the angle at joint \(i\), and \(M\) is the dimension of the force Cartesian space. These last few equations demonstrate that manipulator geometry plays a significant part in determining differential forces due to the occurrence of several forms of the Jacobian. There are in fact four variables that determine the stability of the coupled system: (1) the initial load produced by the manipulator, (2) the initial geometry of the manipulator, which determines its Jacobian, (3) joint stiffness, and (4) the stick Jacobian that relates the differential vector \(dX\) to the angular deviation of the stick.

In Figure 2.9, the manipulator-stick system is stable if:

\[ \left| d\tilde{F} \otimes \tilde{S} \right| \geq \left| \tilde{F} \otimes \tilde{S} \right|. \tag{2.20} \]

With the following relations, \(\tilde{S} = \tilde{R} - dX\) and Eq. 2.17, the equation 2.20 becomes:

\[ \left| K_i dX \otimes \tilde{R} - K_i dX \otimes dX \right| \geq \left| \tilde{F} \otimes \tilde{R} - \tilde{F} \otimes dX \right|, \tag{2.21} \]

and by simplifying we get the condition for stability of the manipulator-stick system:

\[ \left| K_i dX \otimes \tilde{R} - K_i dX \otimes dX \right| \geq \left| \tilde{F} \otimes dX \right|, \tag{2.22} \]

The differential motion \(dX\) is directly linked to the length of the stick, and thus the Jacobian of the stick also influences the stability of the system. This constraint prescribes a local stiffness shape, but does not necessarily constrain regions farther from the point of contact between the stick and the manipulator.
FIGURE 2.9 General planar manipulator pushing on a stick.
2.4 ENERGY BASED ANALYSIS OF A PRISMATIC MANIPULATOR

The force balance analysis used in the previous models requires knowledge of the kinematics of the manipulator and joint stiffness, to estimate the stability of the manipulator. Since this information is not always available, a better approach is to develop the stability model based on the total energy of the manipulator. Assume that the upper limb is made out of kinematic linkages that have inertial properties and it is driven by actuators which are equivalent to springs and dampers. The interaction port, i.e. the hand-stick node thus has apparent stiffness and damping. Assume that the linkage can be described by a generalized coordinate vector $q$ (the configuration space), and that $\dot{q}$ is its derivatives. The total energy of the system $E$ (the sum of the kinetic energy $T$ and potential energy $V$ of the system) is a Lyapunov function if it is positive definite and if $\dot{E}$ is negative definite when $q$ and $\dot{q}$ are non zero (Slotine et al., 1991). Those conditions will be met if both $T$ and $V$ also meet them. The kinetic energy is positive definite and its derivative is negative definite because damping is never negative and it is zero only if joint velocity is zero. If it is assumed that the potential energy is also positive definite, then $\dot{V}$ is negative definite since the hand-stick system can not get stuck at $q \neq 0$ because there would be a force which would move the system away from this point (Slotine et al., 1991).

Figure 2.10 illustrates potential energy fields for some manipulators. Since force is the gradient of the potential field, then the stick must be perpendicular to the energy contour that passes by the contact point if the system is at equilibrium and no friction occurs at the tip of the stick. This ensures the presence of a relative minimum for stability. To the extent that the endpoint motion influences joint motions, a sufficient condition for stability is that the potential energy of the system is positive definite along any joint trajectory that leads to the endpoint displacement. When the stick rotates, the tip follows the contour $E_2$. A system with energy contour $E_1$ would be stable; a system with energy contour $E_2$ has an unknown behavior; and systems with $E_3$ and $E_4$ contours would be unstable. This means that the radius of curvature of the energy contour that passes through the contact point must not be larger than the stick length so that $V$ is positive definite. Figure 2.11 provides an example of a manipulator potential field which would ensure local stability.
FIGURE 2.10 Energy contours of potential fields for different manipulators.

FIGURE 2.11 Energy contours of potential field which can be stable.
FIGURE 2.12 Prismatic manipulator with shoulder stiffness $K_s$ and wrist stiffness $K_w$. 
The stability conditions can also be analytically developed for a prismatic manipulator with shoulder stiffness $K_s$, connected to a stick through a wrist joint with rotational stiffness $K_w$, as shown on Figure 2.12. If the system is slightly disturbed by a distance $dX$ from equilibrium, then the potential energy of the manipulator-stick system will increase due to the assumed stiffness at the wrist and the shoulder joints. Meanwhile, the constant axial force $F$ exerted at the extremity of the stick remains aligned with the prismatic manipulator. This axial force will do a certain amount of work during the motion:

$$W = F \Delta l_m,$$  \hspace{1cm} (2.23)

where $\Delta l_m$ is the change in length of the prismatic manipulator. This change in length can be geometrically obtained:

$$\Delta l_m = l_m \left\{ \left[ 1 + 2 \frac{I_s}{I_m} \left( \frac{I_s}{I_m} + 1 \right) (1 - \cos \theta) \right]^{1/2} - 1 \right\}.$$  \hspace{1cm} (2.24)

For small deviations this equation reduces to:

$$\Delta l_m = l_m \left[ 1 + \frac{I_s \theta^2}{I_m} + \frac{I_s^2 \theta^2}{I_m^2} \right]^{1/2} - 1.$$  \hspace{1cm} (2.25)

If we substitute $A = \frac{I_s}{I_m}$, we obtain:

$$\Delta l_m = l_m \left[ (1 + A \theta^2 + A^2 \theta^2)^{1/2} - 1 \right].$$  \hspace{1cm} (2.26)

But,

$$\sqrt{1 + u} = 1 + \frac{1}{2} u - \frac{1}{8} u^2 \ldots.$$  \hspace{1cm} (2.27)

For small deviations the higher order terms can be neglected and equation 2.26 thus reduces to:

$$\Delta l_m = \frac{l_m}{2} (A^2 + A) \theta^2.$$  \hspace{1cm} (2.28)

For a pulling situation, a similar development yields:

$$\Delta l_m = \frac{l_m}{2} (A^2 - A) \theta^2.$$  \hspace{1cm} (2.29)

The work done by the manipulator represents a minimum bound for the energy the joints must store for a given displacement $dX$. The energy stored at the wrist can be computed as follows:

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\[ F_w = \frac{1}{2} K_w (\theta + \alpha)^2 \]
\[ = \frac{1}{2} K_w (\theta^2 + 2\theta\alpha + \alpha^2) \]

and at the shoulder:
\[ F_s = \frac{1}{2} K_s \alpha^2. \]

For small deviations, we can assume a proportionality between the two angles:
\[ \alpha = \frac{L_s}{L_m} \theta = A \theta. \]

By replacing in the two above equations, we obtain:
\[ F_w = \frac{1}{2} K_w (1 + 2A + A^2) \theta^2, \]

and
\[ F_s = \frac{1}{2} K_s A^2 \theta^2. \]

If the stick and the manipulator are the same length i.e., \( A = 1 \), the equations indicate that the wrist can absorb four times more energy than the shoulder for equal stiffness. Furthermore, if \( A \ll 1 \), then the shoulder has practically no contribution to the stability of the system.

The Lyapunov stability condition can now be expressed as:
\[ F_w + F_s \geq W. \]

Substituting the values of each of the term into equation 2.35, we get:
\[ \left[ K_w (1 + 2A + A^2) + K_s A^2 \right] \frac{\theta^2}{2} \geq FL_m (A + A^2) \frac{\theta^2}{2}, \]

or,
\[ K_w \frac{A+1}{A} + K_s \frac{A}{A+1} \geq FL_m. \]

If the value of \( A \), the ratio of stick length over manipulator length, is substituted back into the equation, we get:
\[ K_w \left( \frac{1}{L_m} + \frac{1}{L_s} \right) + K_s \frac{1}{L_m^2 \left( \frac{1}{L_m} + \frac{1}{L_s} \right)} \geq F. \]
If the wrist stiffness is set to zero and realizing that
\[ K_I = \frac{K_s}{L_m^2}, \quad (2.39) \]
the equation reduces to equation 2.15, as expected.

Similarly, the stability condition for a pulling scenario can be expressed as:
\[ \left[ K_w (A^2 - 2A + 1) + K_s A^2 \right] \frac{\theta^2}{2} \geq F l_m (A^2 - A) \frac{\theta^2}{2}, \quad (2.40) \]
The energy stored at the shoulder remains the same but the one at the wrist is now:
\[ E_w = \frac{1}{2} K_s (\alpha - \theta)^2. \quad (2.41) \]
After simplification, the equation becomes:
\[ K_w \left( \frac{1}{L_m} - \frac{1}{L_s} \right) + K_s \frac{1}{L_m^2} \left( \frac{1}{L_m} - \frac{1}{L_s} \right) \geq F. \quad (2.42) \]
Again, as expected, if we assume zero stiffness at the wrist and substitute equation 2.39, this last equation reduces to equation 2.16, the force equilibrium equation.

The energy based development provides the necessary background to investigate the following two important questions:

- Is it easier to push on a short or a long stick?

- Is there a particular stick and manipulator configuration which makes the task easier for the subject to push on a stick?

From equation 2.38, we define \( C_w \) and \( C_s \) as the coefficients for wrist and shoulder stiffness respectively:
\[ C_w = \left( \frac{1}{L_m} + \frac{1}{L_s} \right); \quad C_s = \frac{1}{L_m^2} \left( \frac{1}{L_m} + \frac{1}{L_s} \right). \quad (2.43) \]
and hence,

\[ C_s = \frac{1}{I_m^2 C_w}. \]  

(2.44)

The higher these coefficients are, the lower is the required joint stiffness to keep the stick stable. If we plot the values of \( C_w \) and \( C_s \) for various manipulator lengths, and stick length/manipulator length ratios, as illustrated in Figure 2.13, it is possible to address the above questions.

Typical values of drill bit length are in the range between .2 and .35 meter. Experimental values of shoulder to hand distance range between .2 and .5 meter. Based on these values, the stick length/manipulator length ratio covers a range from .4 to 1.75. Within this range, we observe that \( C_w \) is generally higher than \( C_s \). A typical value of length ratio is .3/.4, i.e., about .7, with \( C_w \) equal to 6 and \( C_s \) equal to 1. A more meaningful plot is the ratio of the two coefficients illustrated in Figure 2.14. \( C_w \) ranges from 10 times greater than \( C_s \) for a .4 length ratio, to 2.5 times greater for a 1.75 length ratio.

The model thus suggests that it is more efficient to use wrist stiffness, because a lower stiffness is required to accomplish the task, for a practical range of stick length/manipulator length ratios. However, in a human arm, the stiffness about one joint is due to stiffness of muscles that cross this particular joint and the efficiency analysis should be done in the muscle domain. In this case, the analysis must include the effect of the moment arms of the muscles about the joint. A quick analysis can then show that because of the moment arms effects, the wrist stiffness does not seem to be more efficient that the shoulder stiffness. In fact, the moment arms seem to cancel out the wrist stiffness advantage. Given that the required stiffness of the muscles about one joint is

\[ K_m = \frac{K_\theta}{2r^2}, \]  

(2.45)

where \( r \) is the moment arm of the muscle about the joint, one can see that the required muscle stiffness varies to the inverse square of the moment arm of the muscle about the joint. Assuming that \( r \) is about 2 cm for the wrist, and 5 cm for the shoulder, the ratio of muscles stiffness required at the wrist joint compared with the shoulder joint is 6.25, which seems to cancel out the previous kinematic disadvantage of the shoulder. In conclusion, it appears that the simple mechanical model analyzed above can not predict
which strategy, either stabilizing with wrist stiffness or with shoulder stiffness, is more efficient for accomplishing the task.

This stability analysis was developed for a prismatic manipulator whose hand potential field was implemented with both wrist and shoulder stiffness. The energy based analysis can further be applied to any manipulators, since the only required information is the apparent potential field at the hand. This field can be measured experimentally, if analytical computation becomes too complex (Shadmehr et al., 1994).

**FIGURE 2.13** Values of the coefficients $C_w (\cdots)$ and $C_s (\cdots)$ in eq. 2.38. Values are plotted for different manipulator lengths: 1, 2, 3, 4 and 5 meters. Curves with higher values are for shorter manipulators. Typical values of length ratio are from 0.4 to 1.8.
FIGURE 2.14 $C_S/C_W$ ratio of eq. 2.38. Coefficient ratio curve does not vary with manipulator length. Typical values of length ratio are from .4 to 1.8.
2.5 SUMMARY OF MECHANICAL MODELS OF STATIC INSTABILITY

Three different models have been developed: the infinite length manipulator model, the prismatic manipulator model, and the general manipulator model. Stability conditions have been defined using a force equilibrium equation and an energy based approach. The advantage of the energy-based approach is that even if the kinematics or joint stiffness of the manipulator are not known, the potential field at the end point can be experimentally measured, and then used to verify stability by ensuring appropriate curvature such that it is positive definite. The detailed implementation of this field is not necessarily important.

Amongst models analyzed, the prismatic manipulator is probably the closest to reality and its analysis was used to design this doctoral research. The prismatic model showed, in the pushing situation with zero wrist stiffness, that the minimum tangential stiffness required at the end point decreases with the length ratio (stick length)/(manipulator length), and is proportional to the axial force exerted on the stick. The maximum variation of the stiffness occurs inside the 0 to .5 length ratio range. Realistically, a drill length varies between .2 to .4 cm. If we assume a manipulator length of .4, the stiffness constraint changes by a factor of 1.5.

Although the simple mechanical model (infinite length manipulator) of pushing on a stick showed that a "pulling" condition is stable, the prismatic manipulator model has shown otherwise. As the exerted force on the stick changes direction with a change of end point location, it also produces instability. The degree with which the force changes direction, which in turns influences the degree of instability, is solely based on the properties of the manipulator. Therefore, in contrast to initial expectations, when the pivoting point is located behind the manipulator shoulder, it cannot be used as a reference condition for which the impedance selected by the subject is not constrained.
Chapter 3

Upper limb Anatomy, Joint Angles, Muscle Physiology and Force exertion

This chapter describes four topics related to the biomechanics of the upper limb: the upper limb anatomy, the Grood&Suntay technique to measure joint angles and joint axes of the upper limb, a brief review of muscle physiology and a mechanical model to estimate the potential maximum force that a subject can exert on a drill handle. The estimation of joint angles is a very important part of this research because they were used to describe the configuration of the upper limb of drill operators. Joint angles can be defined in numerous ways but for most of the definitions, such as Euler angles, are non-commutative i.e. the sequence of rotations must be specified to uniquely describe the final configuration. This section will describe a method which does not require the specification of a sequence. The section on muscle physiology is provided to better appreciate the effects of selecting a particular posture on the proprioception and joint torque capabilities. Finally, the mechanical model of force exertion will particularly stress the importance of feet placement in the control of the force exerted.

3.1 UPPER LIMB ANATOMY

The upper limb is composed of four main bones: the shoulder girdle (scapula and clavicle), the humerus, the ulna and the radius (c.f. Figure 3.1). Several other smaller
bones from the wrist (8) and the hand (19) complete the list. Bones are interconnected by articulations of different shapes. For instance, the humerus is connected to the scapula at the glenoid cavity. The cavity and the humerus head are spherical, and thus the shoulder joint can be considered as a spherical joint. The scapula itself is actually free to move on the posterior rib cage surface, restrained only by the muscles attached to it, and anteriorly by the clavicle through a spherical joint. There is no cartilage interface, ligament or synovial capsule between the scapula and the torso. The clavicle articulates medially with the superior part of the sternum by a spherical joint.

FIGURE 3.1 Upper limb skeleton, posterior view (Agur, 1991)
The elbow is a more complex joint, although most see it as a simple hinge joint. The elbow is in fact an articulation between three bones: the humerus, the ulna and the radius. Both the ulna and the radius contact the humerus at distinct locations: laterally for the radius and medially for the ulna. The proximal heads of the ulna and the radius move together, during flexion/extension, about the humerus. In addition, pronation/supination of the forearm is produced by a rotation of the radius about its long axis, displacing it slightly over the ulna; the proximal head of the radius has a spherical shape to accommodate both rotations (flexion and pronation). During pronation/supination, the ulna does not undergo any axial rotation, thus, the lateral surface of the radius proximal head is covered with cartilage to provide frictionless motion over the head of the ulna.

The wrist joint is an even more complex joint than the elbow. The wrist is composed of several articulation surfaces at the radius, the ulna, the phalanges and the wrist bones. Pronation/supination occurs mainly at the distal radio-ulnar joint. Flexion/extension and abduction/adduction occur mainly at the radiocarpal and midcarpal joints. Additional motion is also present at other joints: carpo-metacarpal, metacarpophalangeal and interphalangeal (Class notes, Human Functional Anatomy, 1991). The numerous articulations of the hand will not be treated here as they are not specifically of interest to this research.

The main joints of the upper limb (scapula-torso, shoulder, elbow, wrist) are controlled by up to 34 muscles. Every muscle has a specific function, which, in many cases, changes depending upon the upper limb posture. Table 3.1 summarizes the different upper limb muscles, where they originate, their attachment points and type, mono or poly-articular.
<table>
<thead>
<tr>
<th>MUSCLE</th>
<th>ORIGIN</th>
<th>ATTACHMENT</th>
<th>FUNCTION</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapezius</td>
<td>Spine(C7-T12), Occ. prot. head</td>
<td>Spine of scapula</td>
<td>Adduction</td>
<td>S (single joint)</td>
</tr>
<tr>
<td>Latissimus dorsi</td>
<td>Ilium crest. T7-T12</td>
<td>Bicipital groove of humerus</td>
<td>Adduction, Med rotation</td>
<td>2 (two joint muscle)</td>
</tr>
<tr>
<td>Rhomboideus major</td>
<td>T3-T4</td>
<td>Med. bord scap</td>
<td>Adduct., rot.</td>
<td>S</td>
</tr>
<tr>
<td>Rhomboideus minor</td>
<td>C7-T1</td>
<td>Root scap. spine</td>
<td>Adduct., rot.</td>
<td>S</td>
</tr>
<tr>
<td>Levator Scapulae</td>
<td>C1-C4</td>
<td>Top of scapula</td>
<td>Raise</td>
<td>S</td>
</tr>
<tr>
<td>Pectoralis major</td>
<td>Clav., Sternum</td>
<td>Groove humer.</td>
<td>Add., Med rot.</td>
<td>~ 2</td>
</tr>
<tr>
<td>Pectoralis minor</td>
<td>Ribs</td>
<td>Coracoid proc.</td>
<td>Protraction</td>
<td>S</td>
</tr>
<tr>
<td>Subclavius</td>
<td>1st rib</td>
<td>Clavicule</td>
<td>Draws down</td>
<td>S</td>
</tr>
<tr>
<td>Serratus anterior</td>
<td>Ribs</td>
<td>Cost. surf. scap.</td>
<td>Abduct. scap.</td>
<td>S</td>
</tr>
<tr>
<td>Deltoideus</td>
<td>Clavicle, Scapula</td>
<td>Humerus</td>
<td>Abduction</td>
<td>S</td>
</tr>
<tr>
<td>Subscapularis</td>
<td>Scapula</td>
<td>Humeral head</td>
<td>Med. rot.</td>
<td>S</td>
</tr>
<tr>
<td>Supraspinatus</td>
<td>Scapula</td>
<td>Humeral head</td>
<td>Abduction</td>
<td>S</td>
</tr>
<tr>
<td>Infraspinatus</td>
<td>Scapula</td>
<td>Humeral head</td>
<td>Lat. rot.</td>
<td>S</td>
</tr>
<tr>
<td>Teres minor</td>
<td>Scapula</td>
<td>Humeral head</td>
<td>Add., Lat. rot.</td>
<td>S</td>
</tr>
<tr>
<td>Teres major</td>
<td>Scapula</td>
<td>Humerus</td>
<td>Add., Med rot.</td>
<td>S</td>
</tr>
<tr>
<td>Coracobrachialis</td>
<td>Scapula</td>
<td>Humerus</td>
<td>Flexion, Add.</td>
<td>S</td>
</tr>
<tr>
<td>Biceps brachii</td>
<td>Scapula</td>
<td>Radial tuberos.</td>
<td>Flexion, Supin.</td>
<td>2</td>
</tr>
<tr>
<td>Brachialis</td>
<td>Humerus</td>
<td>Ulna</td>
<td>Flexion</td>
<td>S</td>
</tr>
<tr>
<td>Brachioradialis</td>
<td>Humerus</td>
<td>Radius</td>
<td>Flexion elbow, some sup. and pron.</td>
<td>S</td>
</tr>
<tr>
<td>Triceps brachii</td>
<td>Long. head scap. Med. lat. head: humerus</td>
<td>Ulna</td>
<td>Extension, Add. sometime and</td>
<td>S and 2</td>
</tr>
<tr>
<td>Pronator teres</td>
<td>Humerus</td>
<td>Radius</td>
<td>Pron., flexion</td>
<td>S</td>
</tr>
<tr>
<td>Flex. carpi radialis</td>
<td>Humerus</td>
<td>Hand</td>
<td>Flexion wrist and elbow, abd-pron wrist</td>
<td>2</td>
</tr>
<tr>
<td>Palmaris longus</td>
<td>Humerus</td>
<td>Hand</td>
<td>Flexion wrist and elbow, pron. elbow</td>
<td>2</td>
</tr>
<tr>
<td>Flex. carpi ulnaris</td>
<td>Humerus</td>
<td>Hand</td>
<td>Flexion</td>
<td>S</td>
</tr>
<tr>
<td>Flex. digit. superfic</td>
<td>Humerus, Ulna</td>
<td>Fingers</td>
<td>Flexion wrist, elbow</td>
<td>~ 2</td>
</tr>
<tr>
<td>Flex. dig. profundus</td>
<td>Ulna</td>
<td>Fingers</td>
<td>Flexion wrist</td>
<td>~ S</td>
</tr>
<tr>
<td>Pronator quadratus</td>
<td>Ulna</td>
<td>Radius</td>
<td>Pronates forearm</td>
<td>S</td>
</tr>
<tr>
<td>Ext. carpi radialis longus</td>
<td>Humerus</td>
<td>Hand</td>
<td>Ext., Abd. wrist</td>
<td>2</td>
</tr>
<tr>
<td>Ext. carpi radialis brevis</td>
<td>Humerus</td>
<td>Hand</td>
<td>Ext. Abd. wrist</td>
<td>2</td>
</tr>
<tr>
<td>Ext. digitorum</td>
<td>Humerus</td>
<td>Fingers</td>
<td>Ext. wrist</td>
<td>2</td>
</tr>
<tr>
<td>Ext. carpi ulnaris</td>
<td>Humerus</td>
<td>Hand</td>
<td>Ext., Abd. wrist</td>
<td>2</td>
</tr>
<tr>
<td>Anconaeus</td>
<td>Humerus</td>
<td>Ulna</td>
<td>Extension elbow</td>
<td>S</td>
</tr>
<tr>
<td>Supinator</td>
<td>Humerus</td>
<td>Radius</td>
<td>Supinate forearm</td>
<td>S</td>
</tr>
<tr>
<td>Abductor pollicis long.</td>
<td>Ulna, Radius</td>
<td>Hand</td>
<td>Abducts wrist</td>
<td>S</td>
</tr>
</tbody>
</table>

**TABLE 3.1** Muscles of the upper limb.
3.2 JOINT ANGLES vs GROOD & SUNTAY ANGLES

Clinical joint angles are defined as follows:

- **flexion**: angle between the projection of the humerus in the sagittal plane with the long axis of the torso;
- **abduction**: angle between the projection of the humerus in the frontal plane with the long axis of the torso;
- **rotation**: rotation of the *humerus* about its axis.

The shoulder joint angles are shown in Figure 3.2. Similar definitions apply to other joints of the upper limb.

![Diagram of joint angles](image)

**FIGURE 3.2** Illustration of clinical shoulder angles.
Although the classification of joint angles appears to be a simple task, a detailed analysis reveals more difficult issues. Firstly, joint anatomical axes are not necessarily fixed during the course of a rotation. For instance, the scapula can undergo significant translation during movements of the upper limb, thus modifying the location of the shoulder joint axes. A second major problem is that most joint angle representations are non-commutative. A sequence of rotations must be specified to uniquely define a final configuration.

A different representation of clinical joint angles was developed for the knee, by Grood & Suntay (1983), in order to avoid the sequence dependence problem. They take advantage of the fact that the configuration variables of a mechanism, such as a serial robot, uniquely define the orientation of the end effector. This representation is also suitable for any articulation of the human body: it is a special decomposition of the rotation matrix between two body segments. Since it is a representation that was extensively used in this research, it will be explained in the next section.

The advantage of the Grood & Suntay method (1983) is that no sequence of rotations must be specified. The Grood&Suntay angles are: flexion/extension, external/internal rotation and abduction/adduction. The relative motion between two adjacent segments can be represented by a rotation matrix. The joint angles are computed by breaking this rotation matrix into three successive rotations which represent the rotation between one marker, rigidly fixed on the moving segment of the limb, and another marker, rigidly fixed on the stationary segment.

3.2.1 Computing the rotation matrix between two segments in relative motion

Let us assume two segments are connected through a spherical joint, as shown in Figure 3.3. From an initial position, both segments undergo a spatial rotation such that their relative orientation changes after rotation. This relative orientation is given by a rotation matrix $R$ expressed in the $S_0$ reference frame. The matrix $R$ can be determined by first fixing two markers, $M_1$ and $M_2$, on the two segments of interest. Both markers have a local coordinate system, $S_1$ and $S_2$, which are $3 \times 3$ matrices, with column vectors representing the orientation of each unitary vector of the coordinate system, defined in $S_0$. Let us assume that $S_1$ and $S_2$ have a random orientation before rotation occurs.
FIGURE 3.3 Relative rotation of two interconnected segments with randomly oriented markers fixed on each segment. All rotations are expressed in the $S_0$ reference frame.
FIGURE 3.4 Relative rotation of two interconnected segments with fictitious markers
After rotation, both markers reach a new orientation, $S_1'$ and $S_2'$. Since both coordinate systems are not initially aligned with the laboratory reference frame $S_0$, the desired rotation matrix $R$ is not simply the rotation matrix $R_{2' 	o 1'}$ which relates $S_2'$ to $S_1'$.

The matrix $R$ can be obtained by first computing the rotation matrices representing the spatial rotation for each marker, $R_{1' 	o 1}$ and $R_{2' 	o 2}$. These rotation matrices are then applied to fictitious markers $M_{1a}$ and $M_{2a}$, fixed on their respective segments, but with their coordinate systems, $S_{1a}$ and $S_{2a}$, initially coincident with $S_0$; this means that both $S_{1a}$ and $S_{2a}$ are 3x3 identity matrices (cf. Figure 3.4). After spatial rotation of both segments, the two markers $M_{1a}$ and $M_{2a}$ reach a new orientation, $S_{1a'}$ and $S_{2a'}$. The desired rotation matrix $R$ can then be easily obtained, because it is simply the rotation matrix $R_{2a' 	o 1a'}$ which relates systems $S_{2a'}$ to $S_{1a'}$.

In summary, real markers are used to find the rotation matrices that represent the spatial rotation of two segments. These rotation matrices are then applied to fictitious markers, fixed on both segments, but oriented along the laboratory reference frame, $S_0$. The relative rotation between both segments, $R$, is equal to the rotation matrix relating the coordinate systems of both fictitious markers $S_{1a'}$ and $S_{2a'}$ (cf. Fig. 3.4). Since the two segments are not necessarily initially aligned, the rotation matrix, $R$, is not an absolute measure of the relative orientation between both segments. This is the first practical limitation of the Grood & Suntay technique, as they mentioned in their publications (Grood et al., 1983). The joint angles would differ by a fixed offset only.

In practice, for the experiments that were conducted in this research, static files were recorded, where subjects, with markers affixed at various locations on their body, would stand at a given posture which was considered a zero reference for all joint angles. The static files are further described in Chapter 5. Measurements of upper limb joint angles refer to this posture. The precision and accuracy with which the posture can be repeated is actually unknown but clearly significant.

The second practical limitation of the Grood & Suntay technique was not mentioned in their publication. It comes into play when the rotation matrix $R$ must be decomposed in three independent rotations, i.e. joint angles, along "joint anatomical axes".
3.2.2 Decomposition of a rotation matrix into joint angles

The decomposition of a rotation matrix can be represented as a set of Euler angles, or any of several other ways such as Euler parameters, and quaternions (Megahed, 1993) Grood & Suntay angles are also a complete set of configuration variables. Their major advantage is their commutativity property, as opposed to the Euler angle representation, where angles are non-commutative, and hence, a given sequence of rotations produces a different final orientation than another sequence.

Grood & Suntay started from the well known fact that the orientation of the end effector of a serial manipulator is independent of the sequence of rotation of its joints. The problem then reduces to selecting a set of rotation axes to construct a serial kinematic chain, and to compute the joint rotations. These joint angles constitute a vector space which can reproduce any configuration. The Grood & Suntay angles are equivalent to anatomical joint angles only if the set of rotation axes selected is coincident with the joint anatomical axes.

In practice, the anatomical axes are unknown and there will always be a difference between the joint rotations computed and the anatomical joint angles. However, two different ways exist to estimate the anatomical joint axes:

1. by assuming that the markers are initially fixed on the segments in the same orientation as the anatomical joint axes, or,
2. by assuming that the anatomical joint axes are coincident with the laboratory reference frame during the static test taken prior to the experiments.

The first technique is difficult to accomplish when using markers that are fixed on the skin, since we do not really know the orientation of the bones. The second technique offers more accuracy. In fact, it is easier to align the subject with the laboratory reference frame during the static test where reference points are obvious, and the subject, by standing upright in the anatomical position, more or less aligns his anatomical joint axes with the laboratory reference frame (the ground level being a reference plane). This technique has been used in our studies to compute joint angles.

The axes of rotation selected by Grood & Suntay are a set of axes which cross at a common point, without being necessarily orthogonal. They are defined on the basis of the local frames of both fictitious markers after they are rotated. They are defined as follows: (1) a flexion/extension axis which is the $X$ axis of the fixed marker $M_I$, (2) an abduction/adduction axis which is the floating axis $F$; defined as the vector product of the
Z axis of moving marker \( M_2 \) and the \( X \) axis of marker \( M_1 \), and (3) an external/internal rotation axis which is the \( Z \) axis of marker \( M_2 \). The rotations are illustrated in Figure 3.5. The flexion/extension angle is then defined as the angle between axis \( Y' \) of \( M_1 \) and the floating axis. The external/internal rotation angle is defined as the angle between axis \( Y' \) of \( M_2 \) and the floating axis. Finally, the abduction/adduction angle is defined as \( \frac{\pi}{2} - \theta \), where \( \theta \) is the angle between the \( X \) axis of \( M_1 \) and the \( Z \) axis of \( M_2 \).

It is worth noting now that this particular selection of rotation axes is one amongst an infinite number of possibilities. One could suggest a different kinematic chain that would produce the same final rotation in the laboratory reference frame. For instance, the kinematic chain suggested by Grood & Suntay is equivalent to rotating the moving marker about the fixed marker through three subsequent rotations about axes whose orientations are defined by the Euler parameters of each rotation. These three rotations together could be merged to form only one rotation about one axis. The kinematic chain could effectively be replaced by a single hinge joint.

The rotation between two markers is given by a rotation matrix expressed in the laboratory reference frame. Any one rotation can also be expressed by a rotation about a given axis \( \bar{e}_0 \) with an angle \( \theta_0 \). The rotation could also be decomposed into three successive rotations about three different axes, as defined by the Grood & Suntay technique: \( \bar{e}_1, \bar{e}_2, \bar{e}_3 \), with rotations about each axis equal to \( \theta_1, \theta_2, \theta_3 \) respectively. The axes of rotations are illustrated in Figure 3.6. Using the quaternion representation, there is a quaternion that can express every rotation. The quaternions have the following form:

\[
q_1 = a_1 \mathbf{i} + b_1 \mathbf{j} + c_1 \mathbf{k} + d_1 \\
q_2 = a_2 \mathbf{i} + b_2 \mathbf{j} + c_2 \mathbf{k} + d_2 \\
q_3 = a_3 \mathbf{i} + b_3 \mathbf{j} + c_3 \mathbf{k} + d_3 \\
q_0 = a_0 \mathbf{i} + b_0 \mathbf{j} + c_0 \mathbf{k} + d_0
\]  

(3.1)

The rotation of a vector in the laboratory reference frame is given in quaternion notation by:

\[
\mathbf{r}' = q \mathbf{r} q^{-1}.
\]  

(3.2)

The same rotated vector on the moving segment of the hinge can then be expressed in two different ways:

\[
\mathbf{r}' = q_0 \mathbf{r} q_{0}^{-1}
\]  

(3.3)

or,
FIGURE 3.5 Grood & Suntay anatomical axes. Assume that rods connecting each axis have zero length. Axes then meet at a common point. Both, the fixed and moving fictitious segments, have the same origin.
FIGURE 3.6 Decomposition of a single rotation into three successive rotations.
\[
\vec{r}' = q_3 q_2 q_1 \vec{r} q_1^{-1} q_2^{-1} q_3^{-1}.
\]  
(3.4)

Comparing the last two equations gives

\[
q_0 = q_1 q_2 q_3.
\]  
(3.5)

Given the definition of the quaternion product (Appendix A), a relationship can be obtained between the single rotation about the hinge and the three joint rotations defined by the Grood & Suntay technique. Using the general notation of Eq. 3.1 for each of the quaternions, we eventually find,

\[
q_0 = a_0 \hat{i} + b_0 \hat{j} + c_0 \hat{k} + d_0
\]
\[
= [d_4 d_4 - a_4 a_3 - b_4 b_3 - c_4 c_3] +
\]
\[
[d_4 a_3 + d_4 a_4 + b_4 c_3 + c_4 b_3] \hat{j} +
\]
\[
[d_4 b_3 + d_4 b_4 + a_4 c_3 + c_4 a_3] \hat{k} +
\]
\[
[d_4 c_3 + d_4 c_4 + a_4 b_3 - b_4 a_3] \hat{k}
\]  
(3.6)

with,

\[
a_4 = d_4 a_4 + d_4 a_4 + b_4 c_2 - c_4 b_2
\]
\[
b_4 = d_4 b_4 + d_4 b_4 - a_4 c_2 + c_4 a_2
\]
\[
c_4 = d_4 c_4 + d_4 c_4 + a_4 b_2 - b_4 a_2
\]
\[
d_4 = d_4 d_4 - a_4 a_3 - b_4 b_3 - c_4 c_3
\]  
(3.7)

and

\[
a_i = l \sin \left( \frac{\theta_i}{2} \right)
\]
\[
b_i = m \sin \left( \frac{\theta_i}{2} \right)
\]
\[
c_i = n \sin \left( \frac{\theta_i}{2} \right)
\]
\[
d_i = \cos \left( \frac{\theta_i}{2} \right)
\]
The variables $l_i, m_i, n_i$ are the direction cosines of the respective \( \vec{c}_i \) vector about which a rotation $\theta_i$ occurs. Clearly, each of the rotation angles is not linearly related to the hinge rotation angle. This non-linearity could be verified by finding a closed-form solution for each angle. An explicit expression for the relationship between each angle and the hinge angle can not be done. Still, there are analytical solutions. Instead of determining an analytical solution such as the Pieper approach (Yoshikawa, 1990), we chose to investigate the non-linear behavior experimentally.

A short experiment was conducted using the "mechanical elbow" described in Appendix A. The elbow was fixed on a table in front of the cameras. A static file, described in Chapter 5, was then taken with the hinge at about zero angle of flexion, and one marker, fixed on each segment, at a random orientation. Both segments were aligned with the $X$ axis of the lab frame so that the axis of rotation of the hinge was aligned with the $Z$ axis of the lab frame. Data was recorded during rotation of the hinge from 0 to 90 degrees and back to 0. Other static files were also taken, but with the rotation axis rotated at different angles (-33 to 50 degrees) about the $Z$ axis of the laboratory reference frame. Grood&Suntay joint angles were computed using the static files, and results are compared in Figures 3.7, 3.8 and 3.9.

Clearly, the orientation of the hinge axis is important to the static files. Joint angles are not linearly related to the hinge rotation; this non-linearity is better appreciated when the rotation of the hinge is plotted in a 3D space with the Grood&Suntay joint angles in Figures 3.10 and 3.11. When the hinge joint is coincident with an axis of the laboratory reference frame, the locus of rotation follows a straight line along one of the axes in 3D space.

In summary, the orientation of the subject with respect to the cameras, when taking static files, appears to influence the computed joint angles. In fact, the static files define the orientation of the joint axes used by the Grood & Suntay method. Based on our short experiment, however, misalignments of up to 15 degrees do not seem to affect the angles by much. Grood & Suntay angles are but one representation among others, of the rotation matrix between two body segments. The joint angles obtained are accurate, but they are not necessarily the physiological joint angles that are commonly used.
FIGURE 3.7 Flexion angle for positive misalignments $\alpha$ (top) and negative misalignments (bottom). The values of $\alpha$ selected were, in degrees: 3 (considered as the zero reference), 14, 26, 37, 50, -12, -23, -33 and -39. Curvature of the curves increases with magnitude of misalignment $\alpha$. The exception is the -39 case which has lower curvature than -33.
FIGURE 3.8 External/Internal rotation angle for positive misalignments $\alpha$ (top), and negative misalignments (bottom). Angles $\alpha$ are showed at the extremity of their respective curves.
**FIGURE 3.9** Abduction/Adduction angle for positive misalignments $\alpha$ (top) and negative misalignments (bottom). Angles $\alpha$ are showed at the extremity of their respective curves.
FIGURE 3.10 Series of curves representing the rotation of a perfect hinge in the 3D joint angle space. Each curve is the locus of the joint angles values during the rotation of the hinge in a given reference frame. Each reference frame is rotated about the Y axis of a nominal frame considered at zero degree. The different frames were located at -39, -33, -23, -12, 14, 26, 37, 50 degrees from the nominal.
FIGURE 3.11 Curves of Figure 3.10 projected in the plane of flexion/extension and external/internal rotation. The locus of angles in the nominal reference frame is the middle line on the zero axis of external/internal rotation.
3.3 MUSCLE PHYSIOLOGY

This section provides some background on muscle structure and mechanics which is particularly relevant to the control of a drill. General information about the subject can be found in several references (e.g. Kandel et al., 1991; Guyton, 1981) and will not be repeated here.

3.3.1 Importance of posture for maximum muscle force production

Muscles are sometimes considered as simple force actuators. The force that a muscle can develop has been shown to be dependent upon the working length of the muscle in relation to its resting length. A graph of a muscle tension curve versus stretched length is given in Figure 3.12. This curve was obtained during isometric activation of the muscle. It appears quite clear that the upper limb posture selected by a subject in performing a given task specifies the upper limb muscle lengths and hence, the maximum isometric force that a muscle should be able to produce. This maximum force varies significantly over the joint rotation range. The length tension curve can not be directly transposed into a angle-torque curve, however, since the moment arm of the muscle about the joint axis is not constant during joint rotation. For instance, geometrical analysis of a cadaver arm by Amis et al. (1979) suggests a linear change of 20 mm to 75 mm for the moment arm at the brachioradialis; the higher moment arm being at 120 degrees flexion i.e. for a shorter muscle length. The action of the moment arm modulation would thus tend to flatten the length-tension curve. Other elbow muscles had different moment arm variations, which produce different patterns of angle-torque curves.

3.3.2 Spring-like properties of muscles

The dotted line on Figure 3.12 explicitly shows that muscles have intrinsic passive stiffness characteristics, induced by stretching of soft tissues. In addition, due to the pattern of the length-tension curve, if a constantly activated muscle were to be stretched from a certain length, the muscle would exhibit a spring-like behavior. Muscle spindle actions, through spinal reflex loops, can influence this apparent spring-like characteristic (Nichol et al., 1976). As a final observation, a muscle with different activation levels will have different length-tension curves, as illustrated in Figure 3.13: thus, muscle "stiffness" can be modulated by muscle motor activation.
FIGURE 3.12 Length-tension curve of a muscle (Guyton, 1981)
3.3.3 Characteristics of spinal reflex loops

Muscle spindle sensitivity has been shown to be dependent on stretch amplitude. From 0 to approximately 100 μm, the spindle response sensitivity increases almost linearly with the amplitude of stretching (Schaafsma et al., 1991); beyond 100 μm, it decreases. Based on Hill’s results, this "yield" would occur at about 0.2% of the muscle resting length (Hill, 1968). For the biceps, a 0.2% stretch would represent an elbow rotation of about 2 degrees, or a displacement of about 1 cm at the hand.

Muscle spindle sensitivity is also frequency dependent. As shown in Figure 3.14, the peak sensitivity occurs at around 100 Hz. This is particularly noteworthy as most vibrations transmitted from power tools are about that frequency. Vibrations applied directly to the muscle have been found to initiate a constant input to the reflex loops, called the tonic vibration reflex (Matthews, 1986). It was observed that vibrations can initiate either the excitatory or the inhibitory reflex loops.

![Graph showing muscle length-tension curves at different activation levels](image)

**FIGURE 3.13** Areflexive muscle length-tension curves at different activation levels (Hogan, 1984).
FIGURE 3.14 Muscle spindle frequency response. Data was obtained in the linear range at various stretch amplitude levels (copied from Schaafsma et al., 1991, data from Goodwin et al. 1975).
1. an increase in activation of the agonist (homonymous) muscle alpha motor signals, and
2. an inhibitory action on the antagonist muscle.

The reflex time delay is approximately 20 msec for the excitatory loop, and 35 msec for the antagonist loop (Matthews, 1986). The gain of the inhibitory reflex appears to be 40% of the excitatory reflex (Matthews, 1986). The excitatory response was no more than 3% of the voluntary contraction level.

There exists some automatic compensation of reflex gain on varying the pre-existing level of motor discharge (Matthews, 1986). The experimental results suggest that the gain is adjusted to maintain a fixed ratio between the reflex signal and the alpha motor efferent commands. This ensures that reflex loop effects do not disappear for any level of alpha motor commands. Up to 100N, the sensitivity appears to vary linearly with motor discharge, and saturation of the reflexes was occasionally observed for force levels of about 100N.

3.4 ESTIMATION OF MAXIMUM AVAILABLE AXIAL FORCE

The axial force that a subject can exert on a drill depends on his/her body posture, his/her weight, the coefficient of friction with the ground and his/her muscle capabilities. If it is assumed that friction is high enough, and that muscle force is unlimited, the maximum force that can be exerted on a drill depends on the position of the subject's body center of mass relative to the center of pressure on the floor. An extreme situation is shown in Figure 3.15 (a) where the subject stands straight and tries to push on the drill. In such a situation, the center of mass is then aligned with the center of pressure. If we perform a simple free body diagram of the subject, it is clear that for this particular posture, no muscle action can produce an axial force on the drill without destabilizing the body, pushing the subject backward.

The only way to exert a steady axial force is to lean forward, moving the center of mass ahead of the center of pressure, as shown in Figure 3.15 (b) for example. A force couple is produced which is balanced by the desired axial force on the drill, to keep the subject in equilibrium. It is then clear that one is limited in the amount of axial force that can be produced at one drilling location if the arm posture is restricted to a certain admissible subspace.
FIGURE 3.15 Subjects with different body postures during drilling operation.

FIGURE 3.16 Model of subject exerting an axial force on a drill
Figure 3.15 (c) illustrates a mixed posture where the gravity moment about the contact point of the right foot is balanced by both the action of the axial force and the left foot. When the subject moves the left foot ahead, he or she has the ability to move the center of pressure anywhere between the two feet by distributing the body weight between the two legs. By controlling the center of pressure in relation to the center of mass, the subject sets the desired axial force. The method used in Figure 3.15 (c) is the best way to provide accurate and fast control on the axial force because the center of pressure can be moved quickly, by transferring the body weight from one leg to the other. If one chooses the posture shown in Figure 3.15 (b), a well controlled decrease in axial force can only be achieved by increasing the axial force first, to rotate the body backward.

Based on a moment balance about the point O in Figure 3.16, it is clear that the maximum axial force that a subject can provide for a given height h (assuming a maximum body angle because of limited arm length and limited arm force capacities) is given by:

\[ F_a = \frac{MgH}{2h} \cos \theta. \]  

(3.8)

where M is the mass of the body, H is the height of the body (it is assumed that the center of mass is at midheight) and h is a given height of drilling location. With M = 60 kg, H = 1.7 m and h = 1.5 m, the maximum axial force is:

\[ F_{a_{\text{max}}} = 334 \cos \theta (N) \]  

(3.9)

Figure 3.17 illustrates the value of the axial force versus the tilt angle \( \theta \) of the body.

These results are similar to experimental results from various studies stated by Chaffin \textit{et al.} (1991). He made an exhaustive literature review on pushing and pulling tasks and found that pushing height and friction coefficient with the floor were, as expected, two important parameters that determine the maximum force that a subject can produce. No comments were made though on the importance of the body center of mass location and the feet locations on the ability to control the force exerted. Many studies investigated the hand pushing task while restricting the subject to keep the feet parallel.
FIGURE 3.17 Maximum axial force available for a given tilt angle of the body. Subject of 60 Kg, with shoulder height at 1.5 meter.
Chapter 4

Selection of Upper Limb Posture based on Mechanical Criteria

Because the upper limb has more degrees of freedom than a drilling task requires, drill operators can choose from an infinite number of possible upper limb configurations to perform a drilling task. Some limb variations do not affect hand position and orientation:

1. variation of hand to shoulder distance (called H-S distance); and
2. variation of orientation of the plane that contains the arm and the forearm (called UP-PL plane).

Drill operators may take advantage of this upper limb redundancy to select a particular posture based on certain mechanical criteria. For instance, a common criterion use in robotics to treat redundant manipulators is the minimization of torques at the joints. This criterion is relevant in robotics, as torque is directly related to energy consumption. However, it is not clear that the human "control" system works to minimize energy consumption. In fact, no study has yet proven that one selects a posture to minimize joint torques, or any other optimization criteria during various motor control tasks (Gielen, 1990).

Experimental results from this thesis indicated though, that drill operators selected a repeatable posture for similar drilling conditions. The selection of a particular posture suggest that some regularization might occur based on a mechanical criteria which we tried to uncover in this research. The word regularization is used here, instead of
suggest that some regularization might occur based on a mechanical criteria which we tried to uncover in this research. The word regularization is used here, instead of optimization, because the posture selected may not be based on some optimization; instead, subjects may choose a posture which is related to a certain command or desire, such as choosing a posture such that joint angles are at their midrange, or such that the upper limb is within a certain preferred subspace which has been defined through past experience in interactive tasks. Several regularization criteria can be suggested but only three will be discussed:

1. minimization of joint torques;
2. maximization of manipulability;
3. isotropy condition.

These criteria are widely studied in robotics. Our interest was to figure out if they are as relevant in human motor control.

In order to study these two criteria, we assumed a planar two segment model of the arm, as shown in Figure 4.1. This is a simplified model for the arm but it helps to better appreciate the meaning and characteristics of the mechanical criteria suggested. Practically, the upper limb can be considered as a 2D planar manipulator, whose orientation in space is modulated by the operator.

![Planar two link model of the upper limb](image)

**FIGURE 4.1** Planar two link model of the upper limb
4.1 MINIMIZATION OF JOINT TORQUES

The drilling task involves the production of a significant axial force (around 100N). Drill operators might therefore select a posture that serves to minimize torques induced at the joints. This is the same thing as saying that operators select a posture such that they can produce a maximum force in a defined direction (along the drill axis in this case). Arm posture influences the maximum force that one produces at the hand for three reasons:

- arm posture determines muscle length, and muscle force in influenced by muscle length (cf. Chapter 3);
- arm posture modifies the moment arm to the line of action of each muscle;
- arm posture determines the arm jacobian $J$, defining the hand force for given joint torques as

$$F^f = (J^T)^{-1} \tau.$$

(4.1)

An exhaustive review of human force exertion capabilities has been done by Chaffin et al. (1991). The main conclusions are that the maximum force produced varies with radial distance to the shoulder, and with orientation of the upper limb in the horizontal plane. This is expected since the upper limb Jacobian influences the exerted force. He also presented some experimental results which showed that the maximum exerted elbow moment occurs for a 90 degrees flexion, for the average population, but it could vary between 60 to 140 degrees. These results however were based on pushing on a fixed system with no instability. As drilling involves significant static instability, which must be accounted for when an axial force is exerted, it is not clear that the above results can be applied directly.

Minimization of joint torques is a very common concept in mechanics. When applied to the upper limb, it can yield some interesting results. As arm posture determines the arm Jacobian, torques transmitted to the upper limb joints can vary greatly for a given force magnitude and direction at the hand. Thus, one might select a posture to try to minimize these torques, and in turn to reduce the required muscle forces. The relationship between end point force and joint torques is best visualized by computing the force ellipsoids for different configurations of the upper limb. These ellipsoids represent the direction of maximum end point force for a given norm of joint torques. If we assume that the norm of the joint torques is defined as
\[ \| \tau \|^2 = \tau^T \tau = \tau_1^2 + \tau_2^2 + \ldots + \tau_n^2 = 1 \quad (4.2) \]

and that it is bounded by a unit sphere radius of 1, Eq. 4.1 allows us to transpose this torque spherical constraint into a force ellipsoidal constraint defined by:

\[ \tau^T \tau = J_i^T (J_i K J_i^T) J_i \tau = 1. \quad (4.3) \]

The force ellipsoid depends solely on the geometrical properties of this model. Its principal axes coincide with the eigenvectors of \((J_i K J_i^T)\), and the length of each principal axis is equal to the reciprocal of the square root of the corresponding eigenvalue. The maximum force that can be produced at the end point is along the major axis of the force ellipsoid. Figure 4.2 illustrates the force ellipsoids for different configurations of a planar two link arm model: (1) segments of equal length, (2) longer proximal (humerus) segment and (3) longer distal (forearm) segment. In all three cases, ellipsoids have distinctive orientations. The operator might choose to orient the major axis with the drill axis along which he/she exerts a significant axial force, to minimize the torques in the upper limb joints. If subjects choose a torque minimization strategy for regularizing posture, they should completely extend their arms radially.

It is interesting to observe the difference in variation of force ellipsoids for the three cases. In all cases with a flexion angle greater than 70 degrees, the ellipsoids look pretty much alike. However, for smaller angles between segments, the "longer humerus" case behaves uniquely. At exactly 45 degrees, the ellipsoid becomes a circle and there is an isotropy in force production. This characteristic will be discussed in more detail in section 4.3.

Force ellipsoids can also tell us about the force control quality and force sensitivity of the upper limb. Force is most accurately controlled in the direction of the minor axis - a large change in torque produces a small change in end point force -, which is also the direction of maximum force sensitivity - a small change in end point force produces a large change in joint torque. Thus, extending the arm makes the upper limb more sensitive to changes of orientation of a radially oriented force. This is particularly interesting for the stabilization of a drill.
FIGURE 4.2 Force ellipsoids of a 2 link planar manipulator. Elbow flexion angle (i.e. angle between both segments) is given for each location of the end effector. In all three graphs, the locations of the end effector are identical. In the top right plot, the forearm length is .707 times the humerus length; in the bottom plot, it is the opposite.
Force ellipsoids have been developed for the field of robotics, and not for muscle actuated systems. There is a significant difference between the two systems. For instance, the suggested torque norm assumes that the "cost" of providing a torque is linearly proportional to the torque produced. This is a reasonable assumption since the torque produced by a DC motor is proportional to the input current. For humans however, muscles exhibit a non-linear relationship between activation level and torque. In general, this may change the shape of the force ellipsoids but the main axes would remain at the same orientation. As an example, let us assume that the torque produced by a joint is given by the following equation:

$$\tau = a I,$$

(4.4)

where $I$ is the "activation level" occurring at the joint and $a$ is a constant. Equation 4.3 becomes:

$$J^T J = I^T \left( \frac{J J^T}{a^2} \right) I \leq 1$$

(4.5)

The role of $a$ is to change the magnitude of the ellipsoid only. However, if it is assumed that the torque is related to the activation level by

$$\tau = \tan(I),$$

(4.6)

then the ellipsoid is distorted into a lozenge shape, but the main axes remain with the same orientation, as shown in Figure 4.3.

### 4.2 MAXIMIZATION OF MANIPULABILITY

In robotics, researchers are trying to determine how to control the motion of redundant manipulators. One suggestion is to move the different segments of a manipulator such that the *kinematic manipulability* ellipsoid, or *velocity ellipsoid*, is at maximum volume at any time during the motion (Yoshikawa, 1985). Basically, one selects a posture such that for a given set of joint velocities, there is a maximum end point velocity in a given direction. The manipulability ellipsoids are obtained in a similar manner as the force ellipsoids. Starting with the well known equation

$$\dot{x} = J \dot{\theta},$$

(4.7)
FIGURE 4.3 Distorted force ellipsoids when the relation between torque and current is non-linear: $\tau = \tan(I)$. 

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which relates joint angular velocities and hand velocities, a joint velocity norm can be defined:

\[ \| \dot{\theta} \|^2 = \dot{\theta}^2 = \dot{\theta}_1^2 + \dot{\theta}_2^2 + \ldots + \dot{\theta}_n^2. \] (4.8)

If we constrain the norm to a sphere of radius 1,

\[ \| \dot{\theta} \|^2 = 1, \] (4.9)

we can transpose this constraint to an end point velocity constraint using Eq. 4.7:

\[ \dot{\theta} \cdot \dot{\theta} = \dot{x}(J^T J)^{-1} \dot{x}. \] (4.10)

Again a spherical constraint is transformed to an ellipsoidal constraint for end point velocities, and this ellipse is by definition perpendicular to the force ellipsoid.

The principal axes of the velocity ellipsoid coincide with eigenvectors of \((J^T J)^{-1}\), and the length of a principal axis is equal to the reciprocal of the square root of the corresponding eigenvalue. The highest velocity is obtained along the major axis of the velocity ellipsoid. Assuming a planar two link manipulator, the velocity ellipsoids can be computed for three cases: (1) segments of equal lengths, (2) longer proximal segment (humerus), and (3) longer distal segment (forearm). Velocity ellipsoids for each case are illustrated in Figure 4.4. The ellipsoid orientation changes significantly with small elbow flexion, but remains about the same for large flexion angles. The concept of the manipulability ellipsoid is interesting because it addresses the trade-off between maximum hand velocity and maximum velocity control. The hand velocity is most accurately controlled in the direction of the minor axis, which is also the direction of maximum motion sensitivity of the system, and maximum force production.

The computational method of velocity ellipsoids assumed that the human controller tries to minimize a norm of joint velocities. It also assumed that actuators have similar mechanical characteristics over their whole range of motion. Clearly these concepts do not include any physiological characteristics of the upper limb. The Jacobian is indeed an important aspect of velocity production, but it does not take into account that muscles at different joints can have different mechanical moment arms, rendering different joint velocities for a given muscle contraction speed.
FIGURE 4.4 Manipulability ellipsoids of a 2 link planar manipulator. Elbow flexion angle (i.e. angle between both segments) is given for each location of the end effector. In all three graphs, the locations of the end effector are identical. In the top right plot, the forearm length is .707 times the humerus length; in the bottom plot, it is the opposite.
A manipulability measure was suggested by Yoshikawa (1985) as

\[ w = |\text{det} \ J| = l_1 l_2 \sin \theta_2, \]  

(4.11)

which is a maximum for \( \theta_2 \) equal to 90 degrees. He thus suggested that humans "unconsciously use the arm postures that are optimal from the viewpoint of manipulability".

4.3 ISOTROPY CONDITION

The "longer humerus" case has a distinctive behavior for a 45 degree flexion angle. For this arm configuration, the ellipsoid becomes circular and we have an isotropy condition. Isotropy of a manipulator is said to have a number of advantages, including good servo accuracy, noise rejection and singularity avoidance (Klein et al., 1991). This could explain why in human evolution, the brachial index (Aiello et al., 1990), i.e. the ratio of the forearm length to humerus length, has probably changed over the years (billions of years here). In addition, it is very different from the brachial index of close species. A chronological schematic of the evolution of the *homo sapiens* is given in Figure 4.5 along with a list of brachial indexes.

It is worth pointing out that the particular upper limb *homo sapiens* structure is close to the configuration required to obtain isotropy in the velocity production at the end effector. With a brachial index of .707, the velocity ellipsoid becomes circular for a flexion elbow angle of 45 degrees. Any other brachial index would not provide such isotropy. Could it be that isotropy is a driving force into the evolution of our species? Other authors have already studied the isotropy concept for the design of robots (e.g. Angeles, 1992). Salisbury et al. (1982) also used the isotropy concept to select dimensions of fingers in the course of designing an artificial hand.

Velocity ellipsoids have indicated that there is an isotropy condition which could be convenient for the control of a manipulator. For a human arm however, this isotropy condition is not necessarily obtained if the end point velocity is mapped to the muscle contraction domain. Whether the effect of muscle moment arms act to distort, amplify or cancel out the effect of the Jacobian is not clear.
FIGURE 4.5 Chronological map of human evolution along with the brachial index values (forearm length/humerus length) for different species close to the Homo sapiens. (Aiello et al., 1990).
Chapter 5

Investigation of upper limb posture during the drilling task

This chapter describes the drilling experiment study. The goal was to figure out (1) whether certain biomechanical variables of the task affect the upper limb posture selected by drill operators, and (2) whether the operators may have selected the upper limb posture based on some mechanical criterion. The biomechanical variables investigated were: level of axial force exerted on the drill, drill length and drilling location. Posture was analyzed using several upper limb "geometrical descriptors" such as joint angles and hand-shoulder distance.

Before any conclusions could be drawn from the data, our first concern was to assess the first hypothesis of this research:

HYPOTHESIS 1: Drill operators select a repeatable upper limb posture for similar mechanical drilling conditions.

The validity of this hypothesis was of particular importance to draw inferences on the effects of biomechanical variables on posture. Repeatability of posture was statistically tested by a special technique that uses the Grood & Suntay joint angles of the wrist, the elbow, and the shoulder.

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Based on the experimental results, several questions were addressed:

1. Does posture vary across subjects?
2. Does posture vary with drilling height?
3. Does posture vary with the level of axial force exerted on the drill?
4. Does posture vary with drill length?
5. Is there evidence of a regularization criterion underlying the choice of posture?

We also investigated a second hypothesis, i.e.:

**HYPOTHESIS 2:** *The control strategy used in drilling operation is equivalent to that used in pushing on a pivoting stick.*

This hypothesis was investigated to figure out if other factors than static instability could influence the control strategy selected by the operator. The hypothesis was tested by comparing upper limb postures while one was asked to drill at a given point with the drill turned off or on.

Due to the large amount of data that were acquired in this experiment, only the most relevant results will be discussed. The reader should refer to Appendix F to consult the complete set of data. The next section describes the experimental methods used to study the drilling task. The last section will describe the results and analysis of the data.

### 5.1 METHODS

#### 5.1.1 The task

A general description of the experimental protocol is first given. Detailed information on the hardware will be provided in the next section.

The drilling task experiment extended over a three hour period during which a series of seven tests were performed in the following order:

1. a static test, acquisition of 4 static files (subjects in fixed standing position in front of the cameras) which were used to compute joint angles;
2. a maximum force test; estimation of subject maximum axial force exerted on the drill handle;
3. a warm-up test, subjects drilled 10 holes on a vertical wood panel;
4. a location test; subjects drilled at six predetermined locations;
5. a force test; subjects drilled at two different locations using three different axial force levels on the drill handle (50%, 65% and 85% of maximum exerting force previously estimated);
6. a drill length test; subjects drilled at two different locations using three different lengths of drill bit; and finally,
7. a drill off test; subjects pushed on the drill at various locations, at 65% of MEF, as if there were about to drill but with the drill turned off.

For all drilling tests, the subjects were instructed to pick up a drill located on a chair close by, and to drill at given locations on a stainless steel metal plate. The plate was fixed on a vertical panel mounted on a rolling cart. A global view of the experimental setup is shown in Figure 5.1. While the subject drilled, the body posture was recorded both by an infrared camera system and a video camera. Infrared cameras measured the 3D location of infrared LED markers affixed to the upper limb and the drill (Cf. Figure 5.2). Subjects were allowed to use only one hand to operate the drill and the other hand was not to be used to grab the cart. Subjects were also not allowed to lean the elbow of their drilling arm against their waist. During drilling, the subject was to maintain a predetermined axial force on the drill handle, typically 65% of maximum exerted force (MEF) and occasionally, 50% or 85% of their MEF. The actual axial force produced was fed back to the subject using a visual display constructed of 5 LEDs. This display is described further in Appendix B. No additional instructions were given to the subjects.

Each trial consisted of a 2 to 5 second drilling period. Once the subject had stabilized his axial force on the drill (the experiment supervisor had access to a display showing the real time value of the axial force exerted), the infrared camera system acquired kinematic marker data over a .5 second period at 200 Hz sampling frequency. After each trial, the subject was to put the drill back on the chair, move back a few steps, and sit down on the stool if desired. Between each trial, the subject was able to rest between 20 seconds to a minute, during which kinematic data was stored for postprocessing. Resting periods of about 5 minutes were allowed between each set of tests.
FIGURE 5.1 Experimental setup for the drilling task.
FIGURE 5.2  LED markers mounted on upper limb during drilling task
5.1.2 The apparatus

This section describes the various material used during the experiment. General information will be provided in this section. Further information can be found in Appendix B. The drill used for these experiments was a 1.5 kg, 3/8" Makita power drill model #6510LVR 3.5A. High speed steel drill bits were used with a given length such that the distance between the handle and the drill tip was typically 27 cm, and for the drill length tests, lengths of 22 and 32 cm were also used.

Subjects drilled on a stainless steel metal plate, bolted on a heavy wood panel. The panel was fixed on horizontal metal rods supported by linear bearings. The bearings were fixed on the top of a cart that was positioned and locked in place at a slight angle in front of the infrared cameras. A Barry & Wright FS6-120A 6 axes force sensor prevented the board from sliding toward the cart while subjects were drilling. Only the axial force perpendicular to the board was measured by the cell.

The force cell sampling rate was set to 200 Hz. The axial force signal was fed back to the subject using an LED digital display. The display was equipped with 5 LEDs which would turn on at different levels of axial force: the top LED turns on at the lowest force and the next lower LEDs gradually turn on while the axial force is increased. The task consisted of operating the drill at a force level sufficient to keep the first three LEDs lighted (Cf. Figure 5.3). The variation of force between LED 2 and 3, and LED 3 and 4 was in the order of 10 N but would vary slightly depending on the axial force required. This was because each LED would turn on at a fixed percentage of the maximum exerted force (MEF). The LED display was fixed at the center of the drilling panel, ensuring that subjects did not modify their body posture to look properly at the LEDs.

In order to avoid instability of the drill bit tip on the metal surface, starter holes were pre-machined into the metal plate at pre-determined locations. The torque transmitted by the metal plate to the drill bit was very small and practically insensitive to the orientation of the drill because the drill bit was unable to dig into the high strength stainless steel plate. Hence, the drilling conditions did not change even after drilling at the same spot several times.
FIGURE 5.3 LED digital display for force feedback.

FIGURE 5.4 Validation of force measuring system by application of a known force at locations 1, 2, 3 and 4.
Because of the particular design of the system which measured the axial force exerted by a subject on the drill handle, the application of a given axial force on the panel at different locations would produce slightly different load cell readings. This anomaly is mainly due to the occurrence of friction from the linear bearings that hold the panel. The measuring system was validated by applying forces of various magnitudes on the vertical panel at locations 1 to 4. The forces were applied with the end part of a one axis force cell. Readings from the one axis force cell and those from the 6 axis force cell behind the panel were compared. Results are presented in Figure 5.4. Two sets of tests were performed at location 2 and only one set at locations 1, 3 and 4. Although the technique used to produce forces on the panel is not perfect, results show that data collected from location 3 are pretty much along the 45 degree line, this can be explained by the fact that location 3 is at the height of the connection rod between the 6 axis force cell and the panel. Both curves from location 2 are very close to each other, demonstrating the repeatability of the measuring system. Data from other locations than location 3 have either offsets or slightly different slopes, these deviations are probably due to the presence of friction at the linear bearings. The variations in the force readings are however not critical for the research since no quantitative comparative studies were made between drilling locations of different heights.

The rolling cart was supported by locking wheels which had a certain compliance. That compliance, added to the compliance of the panel mounting fixtures, would be sufficient to produce motion in the order of 2 to 5 millimeters when pushing on the panel with the drill. The compliance of the panel was negligible at locations 2 and 3 since they were in the panel area where the rod connects the panel to the 6 axis force cell.

Infrared markers were mounted on the subject body at the following locations: the drill, the forearm, the elbow, the arm, the shoulder and at the tip of a special mounting structure that follows the motion of C7 vertebra (Cf Figure 5.2). The exact fixation technique for each marker is described in Appendix B. These markers were used to monitor the upper limb posture using infrared SLOPSOT cameras and a software called TRACK. This kinematic measuring system is described in detail in Appendix A. The resolution of the system is down to .25 mm, and the precision is in the order of .5 mm. Cameras were sampling at 200 Hz for a period of .5 second during which the subject posture was considered stable. A video of the subject was also taken to provide a global view of the experiment history. Eight subjects were studied in this experiment and their
characteristics are listed in Table 5.1. Each subject had to read and sign an informed consent document, included in Appendix E.

5.1.3 The seven tests performed

TEST 1: Static test

Reference static files were required to compute upper limb joint Grood & Suntay angles as explained in Appendix A and Chapter 3. Subjects were asked to position their body and upper limb parallel to the camera field of view, selecting a posture that was considered as zero degree reference for the joint angles. The position and orientation of the markers were then measured with the infrared cameras, sampling at 200 Hz for .5 second. An average of the 100 data points was then computed to define a unique reference posture. Two different reference static files were measured, they are illustrated in Figure 5.5. Each static posture was measured twice to ensure availability of good data. Although the orientation of the markers on the upper limb segments is not important, the orientation of the upper limb is very important during the static tests. Whenever possible, the joint axes of any one joint have to be coincident with the laboratory reference frame. A complete discussion on the subject can be found in Chapter 3.

TEST 2: Maximum force test

Subjects were instructed to maintain a given axial force on the drill during all the experiments. A medium force level was selected to avoid fatigue. In section 2.6, it was explained that the maximum force that a subject can produce depends on the subject weight as well as the height at which he/she is drilling. The maximum exerting force (MEF) was thus estimated by asking subjects to drill at the highest hole on the metal plate while exerting their maximum axial force on the drill for a period of about 5 seconds during which the axial force signal was recorded. Two to three trials were performed and the average of the force data was computed to determine the maximum force level of the subject. The medium force level was obtained by taking 65% of MEF.
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**TABLE 5.1** List of subjects and their characteristics for the drilling task.

**FIGURE 5.5** Static file body postures: horizontal posture (left), vertical posture (right).
TEST 3: Warm up test

Subjects were asked to drill 10 holes, in the wood panel in the area to the right of the metal plate, for right-handed subjects, or to the left, for left-handed subjects. No restrictions were mentioned on the axial force exerted on the drill or the drilling location. Subjects were to put the drill back on the chair, and step back a few steps after drilling each hole. Upper limb posture and axial force exerted were recorded for each trial. No force feedback was given to the subject. The purpose of this test was to get the subject familiar with the operation of the Makita drill.

TEST 4: Location test

The purpose of the location test was to assess the repeatability of upper limb posture when drilling at a given location under similar mechanical conditions. Repeatability of posture was tested by asking subjects to drill at six different locations on the metal plate as shown in Figure 5.1. The plate is illustrated in Figure 5.6 which shows the six different locations, numbered from 1 to 6. These locations were selected in order to force postural variations and to analyse how subjects would adjust their arm posture. The six locations are grouped in two vertical columns, distanced by 20 cm from each other. This distance was selected such that it is several times the standard deviation of the shoulder position encountered when the subjects were asked to drill at a same location. In the first column, there were four locations. Each location was set at a given distance from the others and it was defined on the basis of the subject anthropometry. The second point from the top was set at the subject shoulder height. The top one was at a distance $Y_1$ from the shoulder level, equal to 20% of the subject maximum arm reach. The lower two were set at a distance $Y_2$ and $Y_3$ equal to 50% of the subject arm length. There were no special reasons to select these distances other than to keep the drilling location in a limited range such that (1) LED markers attached to the upper limb would stay in the range of views of the cameras, and (2) the subject would not need to bend the knees or use an object to raise their body to a comfortable height. Only two locations were chosen for the left column. The second column served as a comparison test for arm posture. Similar arm postures should be expected in each case since they differ by only a horizontal translation.
Subjects were instructed to pick up the drill and start drilling for 3 to 5 seconds at a given location that randomly varied from trial to trial. Five tests per location were performed, for a total of thirty. After each test, the subjects put the drill back on a chair, moved back a few steps and sat on the stool if desired.

TEST 5: Force test

Subjects were asked to drill at locations 2 and 3 only, at three different force levels: low, medium and high. Since the medium conditions had been tested in the location test experiment, it was not repeated here and only low and high levels were tested. Low and high were defined in relation to the maximum force level that had been determined previously. Low was defined as 50% of the maximum force level, and high as 85%. Force feedback was given to the subject and the force cell gains were adjusted such that the task remained the same i.e. to maintain the first three LEDs lighted while drilling.
The subjects were instructed to pick up the drill and start drilling for 3 to 5 seconds at a given location (point 2 or 3) that randomly varied from trial to trial. The force cell gains were randomly changed such that the axial force required to turn on the third LED varied from trial to trial. Five tests were performed per experimental condition, for a total of 20. After each test, the subjects put the drill back on a chair, moved back a few steps and sat on the stool if desired.

TEST 6: Drill length test

There is a minimum drill length that can be tested because of the length of the drill body itself. The lengths selected were: 22 cm, 27 cm and 32 cm. Since the medium size drill had been used in the location test experiments, it was not repeated and only the short and long drills were tested in this experiment. Longer drill bits exist (e.g. 12" long drill bits), but with the magnitude of axial force exerted on the drill, those would buckle and possibly break.

Subjects were instructed to pick up the drill and start drilling for a 3 to 5 seconds at a given location (point 2 or 3) that randomly varied from trial to trial. The force cell was tuned such that the subject had to exert a medium force level to keep the third LED on. Once a drill bit was selected, five tests were performed at points 2 and 3 before the other drill bit was installed. The order of selection of short or long drill was randomly selected from one subject to the another. After each test, the subjects put the drill back on a chair, moved back a few steps and sat on the stool if desired.

TEST 7: Drill off test

A seventh and last test was performed where the subjects were asked to act as if they were drilling but the drill was turned off. This test was performed in order to assess the second experimental hypothesis stated at the beginning of this chapter: similarity of control strategy between drilling and pushing on a stick. Five tests were conducted for each of the points 1 to 4 of the metal plate, at 65% of MEF. Locations were randomly selected from one trial to the other. After each trial, the subject had to put the drill back on the chair, and step back as previously described.
5.1.4 Data analysis

The upper limb posture of drill operators can be described in a number of different ways called "geometric descriptors". These are listed in Table 5.2. Several "descriptors" were analyzed in order to provide on one hand, statistical tools to address both hypotheses, and on the other hand, parameters which are easy to interpret physically. The latter constitute the basic information used to address different questions on posture which were listed at the beginning of this chapter. The various "descriptors" of upper limb posture can be divided into three different groups:

1. those which do not exclude the variations due to global alignment of the operator about the drill tip; as a matter of fact, operators were free to align their whole body and drill within a certain range of horizontal orientation about the drill tip (beyond a certain point though, the drill bit would slip out of the starter hole).

2. those which exclude the variations due to this global alignment; and finally,

3. the one which describes how well subjects respected the constraint of aligning the drill perpendicular to the board.

A brief explanation of each upper limb descriptor will follow. Some examples will also be provided. These descriptors will then be used to address the research hypotheses and questions on posture.

Stick plots

Stick plots are probably the easiest way, after the video, to globally visualize the posture of drill operators. The stick plots are line segments that connect various reference points of the drill, the elbow, the shoulder and the C7 markers. The drill is plotted using 3 points computed on the basis of the drill marker. The elbow and the shoulder markers are plotted as is. For the C7 marker, the location of the C7 vertebra was plotted instead. it was computed based on the C7 marker location. Three kinds of plots are presented: a top view of the subject (Cf. Figure 5.7), a frontal view looking at the subject from behind the vertical panel, and a lateral view. Examples for one subject are illustrated in Figure 5.8. The panel is plotted as a box shape in the lateral view and top view plots. Plots either contain data from all trials or the average of all trial data from the same test conditions. The averaged of the data from Figure 5.8 are shown in Figure 5.9. When a marker does not provide good data, the line segments that connect to this marker are omitted and markers standing alone are represented by a circle. Each marker location is computed by taking the average over a window of data selected from the 100 points recorded per trial.
TABLE 5.2 List of upper limb posture descriptors used in the study.
FIGURE 5.7 Schematic of the three views selected to graphically represent upper limb posture.
FIGURE 5.8 Stick plots for subject 6. Top view (top right plot), frontal view (bottom left plot) and lateral view (bottom right plot) of the subject during drilling location task. Data from all trials, location points 1 to 4 (solid line) and 5 and 6 (dashed lines).
FIGURE 5.9 Average stick plots for subject 6. Top view (top right plot), frontal view (bottom left plot) and lateral view (bottom right plot) of the subject during drilling location task. Data from all trials averaged, location points 1 to 4 (solid line) and 5 and 6 (dashed lines).
All points from every marker are manually analyzed to restrict the window to valid points. Stick plots for all subjects tested are presented in Appendix F. They were mainly used to observe trends, and suggest more specific analysis such as marker dispersion, hand-shoulder distance etc. They were also useful in identifying bad data points.

Marker dispersion

Stick plots have clearly shown that there exist some variations in upper limb posture from trial to trial. The magnitude of these variations was obtained by computing the dispersion of every marker for similar drilling conditions. The dispersion is estimated with the square root of the eigenvalues $\sigma_1$, $\sigma_2$, $\sigma_3$ of the covariance matrix of the marker locations. The largest element indicates the standard deviation in the direction of maximum variation, and the lowest, the standard deviation in the direction of least variation. Tables 5.3 to 5.6 provide these standard deviations for one particular subject, for each marker and for all tests performed i.e. the location test (Cf. Table 5.3), the force level test (Cf. Table 5.4), the drill length test (Cf. Table 5.5) and the static test (Cf. Table 5.6). The ratio of each standard deviation to the maximum standard deviation is also given. The standard deviations are normally computed over only 5 data points and obviously, should be analyzed with care. The tables provide a lot of data for one subject. The data can be reduced by keeping only the mean and maximum values of the standard deviation of each marker, for a given test. For this particular subject, the reduced data is given in Table 5.7.

Drill orientation: horizontal (VDRh) and vertical (VDRv) angles

Although the drill must stay more or less normal to the metal plate while in operation, there is some freedom to deviate from this task constraint. These variations might produce different global alignments of the operator. The orientation of the drill axis is a convenient way to describe the orientation of the drill about a normal vector to the metal plate. Two angles determine the drill axis orientation: (1) a horizontal angle VDRh, which is the angle between the normal vector and the projection of the vector along the drill axis on a horizontal plane, and (2) the angle between the normal vector and the projection of the vector along the drill axis on a vertical plane. The VDRh angle is illustrated in Figure 5.10.
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**TABLE 5.3** Standard deviations for each marker, for every drilling point in the location tests. Data in meters. Subject s6.
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**TABLE 5.4** Standard deviations for each marker, for drilling points 2 and 3 in the force tests. L2 = low force level pt 2; M3 = medium force level pt 3; H2 = high force level pt 2, etc. Data in meters. Subject s6.
<table>
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**TABLE 5.5** Standard deviations for each marker, for drilling point 2 and 3 in the drill length tests. s2 = short drill pt 2; m3 = medium drill pt 3; l2 = long drill pt 2, etc. Data in meters. Subject s6.
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**TABLE 5.6** Standard deviations for each marker, for drilling point 2 and 3 in the drill off test. $S1 = \text{off pt 1}; S2 = \text{off pt 2}; S3 = \text{off pt 3}; S4 = \text{off pt 5}$. Data in meters. Subject s6.

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**TABLE 5.7** Reduced standard deviation table for each marker and for all tests. Data in meters. Subject s6.
FIGURE 5.10 Various upper limb descriptors defined in the horizontal plane. Top view of drill and upper limb.
VTS angle

During drilling, subjects might choose a posture which tries to minimize the torques produced at the shoulder. Evidence of such minimization can be found by analyzing the VTS angle defined between a normal vector to the metal plate and the projection of the vector connecting the drill tip to the shoulder marker in the horizontal plane. The VTS angle is illustrated in Figure 5.10.

VTE angle

Similarly, we can define the VTE angle which is the angle between a normal vector to the metal plate and the projection of the vector connecting the drill tip to the elbow marker in the horizontal plane. The VTE angle is illustrated in Figure 5.10.

VTSVDR angle

Assuming that the force produced by the operator on the drill handle is aligned with the drill axis, and since the drill is not always aligned with the normal vector to the metal plate, a more meaningful angle to investigate shoulder torque minimization is the VTSVDR angle. It is defined as:

\[ \text{VTSVDR} = \text{VTS} - \text{VDRh} \]

The VTSVDR angle is illustrated in Figure 5.10.

VTEVDR angle

Similarly, we can define the VTEVDR angle to investigate minimization of elbow torque:

\[ \text{VTEVDR} = \text{VTE} - \text{VDRh} \]

The VTEVDR angle is illustrated in Figure 5.10.

The following upper limb descriptors remove the effects of global alignment of the subject about the drill tip.

Grood & Suntay angles

Standard deviations of markers have shown that although posture seemed similar from trial to trial, there are significant variations which were partly due to global alignment variations of the subject about the drill tip. Elimination of these global rotations can be
realized by computing the rotation matrix which describes the relative orientation of two markers fixed on adjacent upper limb segments. Rotation matrices are composed of nine elements which can be reduced to three variables: the Euler parameters. These are composed of a rotation angle of one segment relative to another (1 DOF), about an axis oriented in the 3D space (2 DOF if the direction cosine representation is used to define the axis). Therefore, a complete set of configuration variables would require nine parameters if it is assumed that the upper limb has three spherical joints. Euler parameters are however not physiologically meaningful.

A more "practical" decomposition of the rotation matrix can be done with anatomical joint angles using the Grood&Suntay decomposition described in Chapter 3. Once the joint angles are computed, the state of one articulation can be plotted as a point in a 3D angle plot. An example of such a 3D plot is given in Figure 5.11. Each point coordinate is determined by the flexion/extension angle, the external/internal rotation angle and the abduction/adduction angle. Data are plotted for the wrist, the elbow and the shoulder for all location drilling tests of a given subject. Markers used to compute Grood & Suntay angles were markers 1,2,4,6.

Angle points of one joint seem to be clustered in a one dimensional space. This peculiar characteristic is understandable for the elbow since it is almost a hinge joint. The Grood&Suntay angle of a hinge joint was discussed in chapter 3 and the one dimensional nature of a hinge joint angle trajectory in a 3D angle plot was clearly demonstrated. Shoulder and wrist joints are however tridimensionnal joints, and there are no obvious reasons which would reduce their dimension, other than from point 1 to point 4, the hand was following a vertical straight line.

Grood & Suntay angles are convenient to investigate variations of upper limb posture with statistical tests. For instance, in Figure 5.11, it is obvious that for any of the three joints, the cloud of points for location 1 is different than the one for location 4. One may want to provide statistical power to this comparison using 3D statistical techniques. However, due to the small number of points available per condition (typically 5), a 3D comparison would not be significant. We can increase the power of the statistical test by taking advantage of the one dimensional nature of the point distribution in the 3D angle space, when changing from location 1 to location 4.
FIGURE 5.11 3D angle plot for all drilling location tests of subject 6. Data from locations 1 to 6 are plotted. Top left plot: 3D representation of wrist, elbow and shoulder angle locus, top right plot: 3D representation of wrist angles; bottom left plot: 3D representation of elbow angles; bottom right plot: 3D representation of shoulder angles.
If it is assumed that a straight line (in this case, the main eigenvector of the cloud of points) can be fitted to the data of one joint, it is possible to find the projection of each data point on this line and to compare the results on a one dimensional space. The projections of the angle points of Figure 5.11 can be seen in Figure 5.12. The statistical tests were performed on the data after they were referenced to a zero point located on the main eigenvector. This zero point was chosen as: (1) the mean of the projected angles of location 4 for the LOCATION and DRILL OFF tests, (2) the mean of the projected angles of location 3, medium force, for the FORCE test and finally (3) the mean of the projected angles of location 3, medium length drill, for the LENGTH test. The "referenced" projected angles are called the "linear joint angles".

The wrist linear angles, the elbow linear angles and the shoulder linear angles produced by the data of Figure 5.12 are plotted in Figure 5.13. Although the "linearization" technique is not exact for a curved manifold in joint space, it is still a conservative comparative technique since the projection of the data along one line has the effect of bringing the data closer to each other. All other joint angle plots for different conditions and different subjects are provided in Appendix F.

Grood & Suntay angles are a complete set of configuration variables which are accurate and reliable within a subject. However, they do have disadvantages:

- they do not necessarily represent the physiological joint angles that one might want since during the static file, the orientation of the subject must be such that the subject joint axes are coincident with the laboratory reference frame; this is a difficult situation to achieve;
- since the angles are computed from the relative orientation of two markers mounted at the skin surface of the subject, skin motion and muscle shape variations can induce rotation of the markers which is not related to the motion of the bone segments; those variations were assumed to be constant over the experimental period, and finally,
- since markers are not fixed in the exact same manner between subjects, and since skin motion and muscle shape variations are also not the same, comparison of Grood & Suntay angles across subjects is not meaningful.
FIGURE 5.12 3D angles projected along the eigenvector with largest eigenvalue. Data of Figure 5.11. Top left plot: 3D representation of wrist, elbow and shoulder angle locus; top right plot: 3D representation of wrist angles; bottom left plot: 3D representation of elbow angles; bottom right plot: 3D representation of shoulder angles.
FIGURE 5.13 Wrist, elbow and shoulder linear angles after referencing the projected angle points to a zero reference on the eigenvector (in this case, the mean value of location 4 points), location test data of subject 6.
Elbow flexion angle (EF)

The elbow flexion angle heavily influences the mechanics of the upper limb. As previously discussed in the Grood & Suntay angle description, the elbow flexion computed with the Grood & Suntay technique is difficult to interpret, because skin and muscle induced motions of the markers are not related to skeletal motion. Therefore, a technique different than Grood & Suntay is required to compute that angle. Markers 1 (drill handle), 3 (elbow) and 5 (shoulder) fixed on the upper limb can be used to estimate the elbow flexion angle by finding the angle between the vector connecting markers 3 to 1 and the vector connecting markers 3 to 5.

Hand-shoulder distance (H-S)

Drill operators have some freedom to select a particular distance between the hand and the shoulder marker, called the H-S distance. If the upper limb is viewed as a two link segment similar to the one treated in Chapter 4, it is clear that the H-S distance modifies the mechanical properties of the manipulator. The hand location was computed on the basis of the drill marker location. Although the H-S distance is directly related to the elbow flexion angle (EF) within a subject, it is not across subjects.

5.2 RESULTS

5.2.1 Research hypotheses

The first step in the analysis of posture was to assess the first hypothesis of the research:

HYPOTHESIS 1: Drill operators select a repeatable upper limb posture for similar mechanical drilling conditions.

In fact, if drill operators select a particular control strategy based on some mechanical criterion, it is expected that this strategy would result into repeatability of posture. If posture was not repeatable, further investigations would be problematical.

The hypothesis was tested using different upper limb descriptors. The first step was to observe if large postural variations occurred during any of the location, force, drill length and drill off tests. The stick plots, presented in appendix F, show that drill
operators generally maintain similar posture for a given drilling condition. Larger variations occur in some subjects but the largest variations observed were due to the global alignment of the operator about the drill tip. A first measure of repeatability of posture was obtained using the marker dispersion parameter. The reduced tables of standard deviations of all 6 marker locations in 3D space is presented in Table 5.8. This table can be summarized by observing that for all drilling conditions and all subjects, the markers 1 to 4 stay within a sphere of 4 cm radius (one standard deviation sphere). Markers 5 and 6, which are farther away from the drill tip, stay within a sphere of 6 cm radius. Postural variations of this magnitude induce very small changes in the Jacobian and therefore, in the mechanics of the upper limb. The marker dispersion measure does not however remove the variations due to the global alignment of the operator.

The hypothesis was therefore tested using a statistical test on the Grood & Suntay "linear" angles which are not affected by a global alignment of the operator. The reader should refer to the previous section to understand how the nine angles of the upper limb joints can be condensed into only three "linear" angles: the wrist linear angle, the elbow linear angle and the shoulder linear angle. Plots of linear angles for all subjects and all location tests are presented in Appendix F.
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**TABLE 5.8** Standard deviations of each marker location for all drilling tasks performed, for all subjects. Data in millimeters. Values obtained from the covariance matrix of the marker locations in 3D space.
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**TABLE 5.8** Standard deviations of each marker location for all drilling tasks performed, for all subjects. Data in millimeters. Values obtained from the covariance matrix of the marker locations in 3D space. (cont'd)
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**TABLE 5.8** Standard deviations of each marker location for all drilling tasks performed, for all subjects. Data in millimeters. Values obtained from the covariance matrix of the marker locations in 3D space.
The hypothesis was assessed by comparing linear angles between drilling points 2 and 5, and between points 3 and 6. These points only differ by a horizontal translation and hence, similar postures should be observed if only the mechanics of the task matters. Statistical tests were performed on each joint linear angle and results are compiled in several charts located in Appendix F. A student Welsh t test was used because of the assumption of unknown variances. The t value of each test was compared to the critical t values for 2%, 5% and 10% significance. Several critical values were computed since only one value does not tell much about the sensitivity of the test. The tables of t values are somewhat difficult to summarize because of the amount of data involved. This problem can be solved by plotting, for each joint linear angle, the ratios $t_{2\% \, \text{reference/}}$, $t_{5\% \, \text{reference/}}$, and $t_{10\% \, \text{reference/}}$ for each comparison test i.e. locations 2 versus 5 and locations 3 versus 6. Because the data is then significantly condensed, all subject results can be compiled in the same graph as shown in Figure 5.14. Each plot refers to one of the joints. Three bands divided by two solid vertical lines separate results from different tests. The first band contains the t ratios, for all eight subjects, for the comparison of posture between locations 2 and 5. Each vertical cluster of points contains the t ratios of one particular subject. The top point is the 2% t ratio, the middle point is the 5% t ratio and the bottom point is the 10% t ratio. If only one point appears at the ratio value 9.8, this means that all three ratios were over 10. This was done to avoid scaling problems. When subjects had invalid data points, the cluster of three points was not plotted. The horizontal dashed line represents the critical line t ratio = 1. If the t ratios are below this point, the statistical test therefore indicates that the two sample groups are not drawn from the same population. Indeed, the t value would then exceed the critical t value. If one particular t ratio is above the line, for instance, the middle point 5% ratio, this means that the two sample groups are not drawn from the same population, with the chance of making an error of the first kind being 5%. The clusters of points are ordered, from the left to the right of one particular band, as subject 1 to 8. The second band follows the same conventions but the test was the comparison of postures between points 3 and 6. The third band contains the t ratios for the comparison of postures between points 2 and 3. This test was provided to better appreciate the validity of the comparison technique i.e. the technique should be able to tell that subjects used different postures between points 2 and 3, since stick plots clearly demonstrated so.
FIGURE 5.14 LOCATION test condensed plots of student t ratios for the wrist, the elbow and the shoulder. Each vertical cluster of points contains the results of one subject, and it is made of three t ratios in the following order from top to bottom: 2% critical ratio, 5% critical ratio and 10% critical ratio. The horizontal dashed line is to mark a ratio of 1. Points over the critical line mean that the statistical test is not conclusive, under the line, the test indicates that sample groups were from different populations.
Referring to Figure 5.14, one can observe that in almost all cases for every joint, the technique shows that different postures were used between location 2 and 3. If one cluster of points represent one event, one can also observe that over 39 events (combining all plots and data from the first two bands), 75% are located above the ratio = 1 critical line, at a level of 5% or 10% confidence. Most of the clusters below the critical line are from three particular subjects in the comparison test between location 3 and 6. Based on this analysis, we conclude that the first hypothesis is true, i.e. that postures used to drill at different locations, but with same mechanics involved, are not statistically different.

A similar analysis was performed to investigate the second hypothesis i.e.

HYPOTHESIS 2: The control strategy used in drilling operation is equivalent to that used in pushing on a pivoting stick.

The plots of DRILL OFF test linear angles are located in Appendix F. Statistical tests were also performed to compare posture between drill off and drill on conditions at locations 1, 2 and 3. Location 4 was not tested since it was used to reference all linear angles. Condensed plots are shown in Figure 5.15.

Again, if we consider one cluster as one event, 33% of all events, over a total of 54, were below the critical ratio = 1 line. This number is not high enough to conclude that the control strategy used in drill on and drill off cases is different. In addition, most of the clusters that were below were pretty close to the critical 1 ratio. Analysis of the other upper limb descriptors did not reveal any major differences between both "drilling" conditions. The only descriptor which could be investigated further would be the elbow flexion angle EF. However, the apparent variations are not large enough to significantly modify the mechanics of the upper limb. Therefore, the experimental results suggest that the second hypothesis can not be rejected using postural measurements, i.e. there is no statistical difference between the upper limb posture used in drilling operation and that used in pushing on a pivoting stick.
FIGURE 5.15 DRILL OFF test condensed plots of student t ratios for the wrist, the elbow and the shoulder. Each vertical cluster of points contains the results of one subject, and it is made of three t ratios in the following order from top to bottom: 2% critical ratio, 5% critical ratio and 10% critical ratio. The horizontal dashed line is to mark a ratio of 1. Points over the critical line mean that the statistical test is not conclusive, under the line, the test indicates that sample groups were from different populations.
Summary of results for both hypotheses

1. Based on marker dispersion, it has been shown that the variation of posture observed for the same drilling condition would induce very small changes in the Jacobian of the upper limb, and therefore, in the mechanical properties of the limb.

2. The first hypothesis, concerned with posture repeatability, was tested by comparing postures when subjects were asked to drill at different locations, so that whole body motion would be required to keep the same posture, but with same height, i.e. same mechanics. Experimental results suggest that the hypothesis can not be rejected i.e. that postures used to drill at different locations, but with same mechanics involved, are not statistically different.

3. The second hypothesis, concerned with similarity of control strategy while operating a drill or pushing on a stick (a drill turned off in this case), was tested by comparing postures in both cases at three different locations. Experimental results again suggest that the hypothesis can not be rejected based on postural measurements i.e. that the upper limb posture used in drill off and drill on conditions is not statistically different.

4.2 Research questions on factors that affect upper limb posture

The Grood & Suntay angles have been appropriate for statistical tests in the previous section, but they are less attractive if one may like to interpret patterns or invariances of upper limb posture. The other upper limb posture descriptors described at the beginning of this section have the advantage of being more related to the skeletal landmarks of the drill operator. They are the following:

1. VTS angle: angle between the vector connecting the drill tip to the shoulder and the vector normal to the drilling panel;

2. VTE angle: angle between the vector connecting the drill tip to the elbow and the vector normal to the drilling panel;

3. VDR angles (VDRh and VDRv): the angle between the projection of the vector along the drill axis on a horizontal plane (VDRh) or a vertical plane (VDRv) and the vector normal to the drilling panel;

4. VTSVDR angle: defined as VTS - VDRh;

5. VTSVDE angle: defined as VTE - VDRh;

6. EF angle: elbow flexion angle computed with the markers located no the drill, the elbow and the shoulder;

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7. H-S distance: distance between the shoulder marker and the hand, computed from the
drill marker, and finally,

These descriptors were used to address various questions on what factors affect
the upper limb posture:

1. Does posture vary across subjects?

2. Does posture vary with drilling height?

3. Does posture vary with the level of axial force exerted on the drill?

4. Does posture vary with drill length?

5. Is there evidence of a regularization criterion underlying the choice of posture?

5.2.2.1 Does posture vary across subjects?

The investigation of posture variation across subjects was performed by combining
all postural descriptors from the LOCATION test, for all subjects, on the same graphs.
Results are shown in Figs 5.16 and 5.17. The same technique was used to plot combined
results for FORCE and LENGTH tests, for the VTSVDR, VTEVDR and EF angles, as
shown in Figure 5.18.

The elbow flexion angle (EF) varies between 15 to 140 degrees across subjects.
Each subject seemed to have a preferred range of EF angles; in general, the ranges
extended over 25 degrees within a subject. Five subjects over eight had EF angles over 90
degrees. The mean and standard deviation of EF angles for each subject, over all
LOCATION, FORCE and LENGTH test, are given in Table 5.9. No correlation were
evident with any of the following parameters: arm length, forearm length, limb length,
maximum exerting force (MEF), subject height, subject shoulder height, and subject
weight.
FIGURE 5.16 VTS, VTE, VTSVDR and VTEVDR values, for all subjects, in the LOCATION test.
FIGURE 5.17 VDRh, VDRv and EF values, for all subjects, in the LOCATION test.
FIGURE 5.18 VTSVDR, VTEVDR and EF values, for all subjects, in the FORCE AND LENGTH tests.
<table>
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**TABLE 5.9** Elbow flexion angle (EF) and Hand-Shoulder distance (H-S) means and standard deviations for all subjects, over all LOCATION, FORCE and LENGTH tests.

The values of the hand-shoulder distance for all tests performed are illustrated on plots located in Appendix F. The horizontal dashed line represents the total upper limb length, without the hand. The mean and standard deviation of the H-S distance, over all LOCATION, FORCE, and LENGTH tests, was computed for each subject. The results are given in Table 5.9. The H-S distance varied significantly across subjects. Again, no correlation could be established with arm length, forearm length, limb length, maximum exerting force (MEF), subject height, subject shoulder height, and subject weight.

The VTSVDR and VTEVDR angle variations across subjects is interesting. Although there was only two left handed subjects, results suggest that left handed may tend to align the drill axis with the elbow joint. In fact, all right handed subjects had VTEVDR angles negative, and left handed subjects had VTEVDR angles centered at zero or higher than zero. In contrast, right handed subjects may tend to align the axis with the shoulder joint. Right handed had VTSVDR angles closer to zero or higher than zero, and left handed had VTSVDR angles significantly below zero for most of the conditions. Further experiments should be undertaken to investigate this trend.

The VDRh and VDRv angles, which describe the orientation of the drill axis, suggest that left and right handed subjects demonstrated similar accuracy in positioning the drill: the range of angle variations is generally between +/- 5 degrees, and could be as
large as 20 degrees for the VDRh angle. One may then expect that drill operators usually maintain the drill within +/- 5 degrees orientation.

5.2.2.2 Does posture vary with drilling height?

The Grood&Suntay 3D angle plots clearly show that posture does vary with drilling height for all subjects. Analysis of the geometrical descriptors can tell us more about where variations and invariances occur. Two of these descriptors are of particular interest: the EF angle and the VTSVDR angle.

Except for subjects s2 and s6, the Elbow Flexion Angle (EF) is pretty much constant for any of the drilling heights i.e. points 1 to 4. The range of variation of the EF, within a subject, is around 25 degrees. The EF, for all subjects, varied between 15 to 140 degrees. Because the EF angle is usually in the range of 90 degrees and higher, a variation of 25 degrees induces very small variations in the hand-shoulder distance. That explains why the H-S distance did not vary by much within a subject i.e. generally a 3 cm standard deviation. Results are shown on graphs located in Appendix F. No statistical tests were pursued to investigate H-S variations, with drilling height, since the technique used to estimate joint locations was not very accurate: there was at least a 1 to 3 cm error on the joint location estimation. The important point to observe, though, is that each subjects maintained a given H-S distance, and the small variations with drilling height do not significantly affect any of the mechanical characteristics of the upper limb.

The VTSVDR angle slightly varied with drilling height for all right handed subjects. However, they varied largely for left handed subjects i.e. over 30 degrees. Although the shoulder joint location was estimated based on the shoulder marker, there is still uncertainties in the location of the joint since the marker was not rigidly fixed to the shoulder, neither to the scapula. This could induce artifacts which could explain the small variation of the VTSVDR angle with drilling height, in the case of right handed subjects. However, these would not account for the large variations encountered for the left handed subjects.

Most of the other geometrical descriptors were constant with drilling height. The variation of posture was therefore included in descriptors which were not discussed so far. Analysis of the frontal and lateral views of the stick plots can clearly show where the postural variations occurred:
1. in the vertical orientation of the vector that connects the hand to the shoulder, and
2. in the orientation of the plane that contains the arm and the forearm.
These descriptors should be studied in a future investigation.

5.2.2.3 Does posture vary with the level of axial force exerted on the drill?

Stick plots of all subjects for the FORCE test suggest that drill operators selected a similar upper limb posture for all three levels of axial force. This observation was statistically tested with the Grood&Suntay linear angles, using the same method that was explained in section 5.2.1. The compiled plots of the linear angles, for the FORCE test, can be found in Figure 5.19. Results show that out of 70 events (one event is a vertical cluster of three points), only 16% suggest that the posture selected between two axial force level would be different, at a 5% significance level. We therefore conclude that, for the particular range of axial force studied, upper limb posture is not affected by the axial force exerted. The validity of the statistical test can be appreciated by the following observation on the posture selected between points 2 and 3: out of 12 events, 100% suggest that the posture selected was different.

5.2.2.4 Does posture vary with drill length?

Similarly, stick plots of all subjects for the DRILL LENGTH test suggest that drill operators would select a similar upper limb posture for all drill lengths studied. This observation was statistically tested with the Grood&Suntay linear angles, using the same method that was explained in section 5.2.1. The compiled plots of the linear angles, for the drill length test can be found in Figure 5.20. Results show that out of 121 events, only 14% suggest that the posture selected for different drill length would be different, at a 5% significance level. We therefore conclude that, for the particular range of drill lengths studied, upper limb posture is not affected by drill length. The validity of the statistical test can be appreciated by the following observation on the posture selected between points 2 and 3: out of 20 events, 75% suggest that the posture selected was different.
FIGURE 5.19 Compiled linear angles for the FORCE test.

FORCE TEST STATISTICS

- 2% signif.
- 5% signif.
- 10% signif.

posture invariant

posture statistically different

ratio \( t_{ref}/t = 1 \)
FIGURE 5.20 Compiled linear angles for the DRILL LENGTH test.
5.2.2.5 Is there evidence of a regularization criterion underlying the choice of posture?

Three regularization criteria have been discussed in Chapter 3: the minimization of joint torques, the maximization of manipulability and isotropy condition at the hand. Those were explained using a planar two link manipulator. The experimental results were compared with the results that this model suggested. The planar model has shown that, if torque minimization is the regularization criterion that operators use to select a particular posture, we should expect that they would keep their upper limb completely extended, to zero out the torques at the wrist, the elbow and the shoulder. This is clearly not the situation found in the experiment.

There is a problem, though, with torque minimization; the joint domain must be specified. Our analysis was restricted to the upper limb. A more complex model, including other joints such as the vertebral joints, the hip and the knee joints, could lead to different conclusions. Simpler models should also be considered since results showed that left handed subjects may tend to minimize the torque at the elbow, and right handed ones would tend to minimize the torque at the shoulder.

The minimization of the torque about the shoulder may have some implications with the proprioceptive system. It is well known that the resolution of force sensing goes up when the force magnitude decreases (Jones et al., 1989) We can then speculate for instance, that right handed drill operators may try to reduce the muscle activation at the shoulder, to increase the resolution of the shoulder torque sensing capabilities. Such high resolution can be useful to better sense the changes in force orientation exerted on the drill. This is particularly important since the force produced on the drill should be aligned with the drill axis, to minimize the static instability. Further investigations should be conducted to analyze this concept.

Maximization of manipulability was also suggested as a minimization criterion. The theoretical results of the planar manipulator predict that drill operators should maintain their elbow flexion angle (EF) at 90 degrees to maximize manipulability. Figs 5.17 and 5.18 and Table 5.9 show that the EF angle significantly varies across subjects. Although the EF angle estimation technique is not very accurate, we can state that subjects did not maintain this 90 degree angle.
Referring to the discussion on the brachial index in Chapter 4, some author in the robotics field (Angeles, 1992) suggested that humans would select an upper limb posture such that they could achieve an isotropy condition at the hand, i.e., isotropy in velocity and force production capabilities. Indeed, humans have a brachial index of about .7 i.e., very close to the .707 required to make isotropy possible. From the analysis of Chapter 4, we can easily see that even if one tries to achieve isotropy conditions at the hand, the EF angle should be lower than 90 degrees, more specifically in the 45 degree region. Results from this experiment show that most of the subjects did not choose such a posture.

5.3 DISCUSSION

The drilling task experiment was performed in order to investigate patterns or invariances in the posture selected by drill operators. Results showed that the postural variations encountered, for similar mechanical drilling conditions, were small enough that they may not induce significant variations in the upper limb mechanical characteristics. These results also suggest that some regularization criterion could be used by drill operators to select one posture amongst the infinite possible ones. As subjects seem to use repeatable postures, the investigation was extended to analyse the influence of certain factors on the posture selected: the magnitude of the axial force on the drill and the length of the drill.

Statistical tests have shown that the upper limb posture selected did not vary significantly between different levels of axial force and drill length. This surprising result suggest that if a regularization criterion exists, it may be kinematically oriented. Three kinematically oriented regularization criteria were investigated based on a two link planar manipulator: the minimization of torques, the maximization of manipulability and isotropy condition at the hand. Neither of them have been able to predict the posture selected by drill operators. Obviously, different upper limb models could be tried but it appears very unlikely that a more complex model would be successful. In contrast, the investigation of the minimization of torque about only one joint, either the shoulder or the elbow, seems to be more promising.

We anticipated that posture might vary with the level of axial force and drill length because both factors affect the level of static instability which must be offset by the operator. Hand stiffness can be used to achieve this task, and hand stiffness can be
significantly modified by postural variations. Two different explanations can be given concerning the apparent insensitivity of posture to force and drill length:

1. the comparison technique with linear joint angles was too conservative, and some information was lost in the processing. This could be improved by selecting a different statistical analysis using "spatial regression" techniques, such as the ones used in the analysis of earth plate motions (Rivest, 1991).

2. the range of force magnitude and drill length studied was not large enough to observe significant variations. Two answers can be given to this argument. Firstly, the range of force and drill length studied were in the "reasonable" range encountered in a drilling task. Secondly, if we assume that drill operators use a "manipulator" length of .4 m, and that the prismatic manipulator developed in Chapter 2 is valid, we should expect an increase of static instability by 100% from a long drill with low force, to a short drill with high force. If operators use their hand tangential stiffness to offset the instability, this would imply than stiffness should almost double between the two conditions. Postural variation may then be used to accomplish this new stiffness. However, if the rotational stiffness of the hand is taken into account, the apparent stiffness at the hand might always be sufficient to offset the instability in all the drilling conditions studied. Hence, postural variations would not be required.

The drill off condition was also investigated. Results show, not as clearly as the influence of force magnitude and drill length though, that posture was not statistically different while drilling with the drill turn off or on. This again support the fact that posture may be selected based on the kinematic description of the task.
Chapter 6

Measurement of Hand-Stick Node Stiffness in the Push-on-a-stick Task

It has been suggested that humans would take advantage of their hand mechanical impedance in the course of performing stable motor tasks. In fact, by changing muscle activation patterns, or by changing their arm posture, humans can voluntarily modulate their hand apparent stiffness, damping and inertial characteristics. Evidences of impedance modulation "activities" were observed for example by Murray (1988) and Lacquaniti et al. (1993). They both found that subject hand stiffness increased when subjects were expecting force perturbations on the upper limb. Two questions arise from such observations:

1. do humans voluntarily modulate their hand impedance to fulfill some specific goal? and if so,
2. what are the factors that influence the impedance selected?

In hand-held power drill operation, we believed that subjects would "tune" their hand impedance, more specifically, their hand stiffness to offset the static instability induced by the axial force exerted on the handle.

The purpose of the push-on-a-stick experiment was to investigate the hand stiffness that subjects selected in drill operation. Because of technical difficulties involved in measuring hand stiffness directly during drill operation, it was measured while subjects
were asked to push with a given axial force magnitude, on a drill handle mounted on a pivoting stick (cf. Figures 6.1 and 6.2). This particular situation allowed us to isolate the static instability phenomena from other factors involved in drilling. Results from the drilling task experiment showed that subjects used similar postures when pushing on a drill turned on or turned off. For this reason, we believe that results from the push-on-a-stick task will provide reasonable estimates of the stiffness selected by drill operators.

The hand along with the stick handle form a kinematic chain. With the particular setup used, we could only measure the apparent stiffness at the Wrist Rocket node. Our goal was to obtain estimates of the Wrist Rocket node stiffness ellipsoid, such as those measured by Mussa-Ivaldi et al. (1985) (cf. Figure 1.3), and then infer conclusions on the hand stiffness from this data, since hand-stick node stiffness and Wrist Rocket stiffness are related by a Jacobian transform. By analyzing the size variations of the minor and major axes of the ellipsoid with different levels of axial force exerted and different stick lengths, we addressed the third hypothesis of this thesis which states that:

"In hand-held power drill operation, one selects a particular hand stiffness magnitude to exactly compensate for the static instability induced by the axial force exerted."

The theoretical analysis of this static instability, in Chapter 2, has shown that a minimum stiffness is required to keep the drill stable, but no maximum was prescribed. If subjects choose to adopt the minimum stiffness required, this would mean that the apparent stiffness of the hand-stick node, and hence the Wrist Rocket node should be very close to zero. Other alternatives were also investigated.

1. Subjects select a particular hand stiffness such that the hand-stick node stiffness is kept constant and significantly different than zero.

Subjects may prefer to maintain a constant hand-stick node stiffness different than zero such that, for instance, there exists a fixed stability margin in the system for any instability levels of the stick (McIntyre, 1990). Such stability margin influences the response of the system to perturbations.
FIGURE 6.1 Global view of experimental setup.

FIGURE 6.2 Drill handle mounted on a stick.
2. The hand-stick node stiffness increases or decreases with the level of axial force exerted.

Since muscle stiffness increases with force, hand stiffness also increases at the same time. The rate of increase of hand stiffness is particularly important in the push-on-a-stick task since it must be larger than the rate of increase of the negative stiffness induced by the axial force, such that instability is not reached for any levels of axial force. Depending on the relative magnitude of these rates, the resulting hand-stick node stiffness will increase (hand stiffness rate higher than negative stiffness rate) or decrease (hand stiffness rate lower than negative stiffness rate).

6.1 METHODS

6.1.1 Hardware and protocol

Infrared markers were first mounted on the subject in the same manner as in the drilling task experiment i.e. on the drill, the forearm, the elbow, the arm, the shoulder and at the tip of an extension rod attached at the level of the C7 vertebra. Although all positions of markers were available, only the drill marker data have been used in the analysis. The drill was dismantled in two parts: the front part that contains the gearing and most of the electrical motor was removed; only the handle part was kept. A special mounting system was designed such that a metal rod could be screwed to the handle part along the drill axis. A drill bit was rigidly fixed at the end of the metal rod. A pneumatic force perturbation device was then inserted around the metal rod and moved up to the handle part against which it was rigidly fixed. The device was used to apply step force perturbations on the stick to measure the compliance of the Wrist Rocket node, while subjects were asked to push on the stick with a given axial force.

This pneumatic device, called the Wrist Rocket, is described in Appendix C. It is a system that can produce step force perturbations in discrete directions in 3D space. It is made of 8 air jets, one along the positive and negative directions of two orthogonal axes named $X_w$, $Y_w$, two along each of the positive and negative $Z_w$ axis. The Wrist Rocket can produce step forces in the order of 2.5 to 4 N, depending on the particular air supply hardware arrangements used, and assuming a 115 psi pressure source. Only the air jets along the $X_w$ and $Y_w$ axes were used in this experiment. The Wrist Rocket local $X_w$ axis was directed along the $Y$ axis of the laboratory reference frame (i.e. upward) and the Wrist
Rocket local $Y_W$ axis was along the $Z$ axis of the lab. ref. frame (i.e. horizontally). The Wrist Rocket $Z_W$ axis air jets were blocked in order to increase the thrusts along the $X_W$ and $Y_W$ axes. With the particular hardware setup that was used, the combined action of air flow along the $X_W$ and $Y_W$ axes could create only four possible force vectors in the $YZ$ plane: $F_1$, $F_2$, $F_3$ and $F_4$. These are illustrated in Figure 6.3. By changing the Wrist Rocket force status from one vector to another, a total of 12 step force perturbations could be produced. Those are illustrated in Figure 6.4.

The experimental protocol was the following. Subjects were asked to pick up the drill handle (hanging in the air close to the cart) and to make contact with the drill bit in a small starter hole that was previously made on a metal plate. This plate was bolted at the end of a 6 axis force transducer which measured the axial force produced by the subject. Levels of either 50%, 65% and 85% of their maximum exerting force were exerted by subjects. The force was fed back to the subject using the same LED digital display described in the drilling task experiment and Appendix B. The contact point was set at the level of point 3 of the drilling experiment, i.e. at 50% of arm length under the shoulder height. Subjects were told to push on the drill as if they were drilling; they also had to hold the trigger. They were allowed to use only one hand to hold the drill handle, and the resting hand could not be used to grasp any mechanical parts. The subjects had to maintain the axial force for a period of 12 to 15 seconds during which, after the axial force produced had stabilized, 10 seconds of force perturbations were produced by the Wrist Rocket. Subjects were told "not to intervene with the perturbations". This particular instruction has been shown to produce sensible results in other studies measuring hand stiffness (Won, 1993; Shadmehr et al., 1994).

The force perturbation sequence used is shown in Figure 6.5. At the start, because air was constantly flowing in any one of the two nozzles of the Wrist Rocket, there was always an initial force vector produced. From this particular initial state, a second state was suddenly reached (any of the other three), and the Wrist Rocket then alternated back and forth between these two states, three times during a period of 10 seconds. For the sake of convenience, the force perturbations, from the initial state to the second state, will be called the "UP" perturbations, and the ones from the second state to the initial state, the "DOWN" ones. As there were twelve possible different force perturbations, there were twelve force perturbation sequences of 10 seconds for each of the pushing conditions. A resting period of 30 to 60 seconds was given to the subjects between each perturbation sequence. During the perturbation, the magnitude of the axial force exerted was recorded.
FIGURE 6.3 The four Wrist Rocket force vectors. The dotted square provides a reference to identify the 45 degree directions from the origin.

FIGURE 6.4 The twelve Wrist Rocket step force perturbations created by the four force vectors of Figure 6.3. The dotted square provides a reference to identify the 45 degree directions from the origin. The directions along the axis have two force perturbations each. This is due to the fact that this direction can be reached under two different conditions. For instance, step forces 4 and 10 are reached by switching the Y axis Wrist Rocket piston from one side to the other, while the X axis piston remains respectively in the positive or negative direction.
onset time (sec): 1.5  3  4.5  6  7.5  9

FIGURE 6.5 Force perturbation sequence onset times

FIGURE 6.6 Experimental setup for pulling tests.
and the motion of the markers was captured with the SELSPOT cameras. Most of the
time, the cameras sampled at 50 Hz (some trials were at 100 Hz), which is significantly
over the highest frequency of the drill and upper limb motion due to perturbations. Since
the Wrist Rocket was particularly noisy (115 db), ear plugs and ear cup protectors were
used together. Due to time constraints, only four subjects were tested in the experiment.
They are listed in Table 6.1. Three of these subjects (s11, s12 and s13) also participated
in the drilling task experiment.

The experiment investigated the variation of stiffness under six different pushing
conditions: medium length stick (27 cm) at 50%, 65% and 85% of maximum force level,
and a long stick (50 cm) at the same force levels. The particular conditions studied in
each subject are listed in Table 6.2. Additional pushing conditions were used for certain
subjects, in order to get some idea of the effects of certain parameters: stick centered on
the drill handle to avoid moments on the wrist, pushing at shoulder height (i.e. location 2
in drilling task), higher force level, and pushing on the drill while it was retained by a steel
cable attached at 2 meters behind the subject with an axial force of 50%, 65% or 85% of
the maximum exerting force. This particular setup is illustrated in Figure 6.6.

6.1.2 Procedure used to estimate the Wrist Rocket node stiffness

Since the input perturbation on the stick was a force, and the measured output, a
displacement, this experiment measured a compliance value. As the upper limb and the
stick form a kinematic chain, our experiments measured the apparent compliance of the
chain at the Wrist Rocket (WR) node. Because WR motion induced was generally small,
i.e. in the order of 0 to 10 mm, we assumed a linear compliance and the WR node stiffness
could be obtained by taking the inverse of the compliance matrix. Because the WR node
stiffness depends on the hand mechanical characteristics and the static instability due to the
force exerted on the stick, it was possible to infer some conclusions on the hand stiffness
variations based on the knowledge of the WR node stiffness. The procedure used to
compute the WR node stiffness is the following. A typical drill handle response to step
force perturbations, for a complete sequence, is shown in Figure 6.7a. Vertical lines
represent the time at which switching commands were sent to the Wrist Rocket. The
response shows that the force inputs produced clean step motion of the handle. In
general, the step responses were similar within a sequence. One may argue that subjects
may have voluntarily intervened to the step forces. For control purposes, one subject was
actually asked to intervene, i.e. to maintain the initial location of the hand prior to the
perturbations.

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**TABLE 6.1** List of experimental subjects.

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<td>Long stick, 85%</td>
<td>Long stick, centered handle, 50%</td>
<td>Long stick, centered handle, 85%</td>
<td>Long stick, location 2, 50%</td>
<td>Bad data</td>
</tr>
<tr>
<td>s11</td>
<td>Long stick, centered handle, 50%</td>
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<td>Long stick, 65%</td>
<td>Long stick, 85%</td>
<td>Medium stick, 65%</td>
<td>Medium stick, 85%</td>
<td>Medium stick, 50%</td>
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</tr>
<tr>
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<td>Bad data</td>
<td>Bad data</td>
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<td>Bad data</td>
<td>Bad data</td>
<td>Bad data</td>
<td>Bad data</td>
</tr>
<tr>
<td>s13</td>
<td>Pulling, 65%</td>
<td>Pulling, 85%</td>
<td>Pulling, 50%</td>
<td>Bad data</td>
<td>Bad data</td>
<td>Bad data</td>
<td>Bad data</td>
<td>Bad data</td>
</tr>
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<td>Medium stick, 65%</td>
<td>Medium stick, 50%</td>
<td>Long stick, centered handle, 65%</td>
<td>Long stick, centered handle, 85%</td>
<td>Long stick, centered handle, 50%</td>
<td>Long stick, MAX</td>
<td>Bad data</td>
</tr>
<tr>
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<td>Medium stick, 85%</td>
<td>Medium stick, 50%</td>
<td>Long stick, 65%</td>
<td>Pulling, 65%</td>
<td>Bad data</td>
<td>Bad data</td>
<td>Bad data</td>
</tr>
</tbody>
</table>

**TABLE 6.2** List of experimental conditions for each subject
The resulting handle response, shown in Figure 6.7b, is clearly different and the subject was able to "intervene" and to bring the handle back to its initial position.

The location of the WR, i.e. the center of the WR, was computed based on the location of the drill handle marker. For convenience, the WR trajectory, following perturbations, was rotated so that it mainly occurred in the YZ plane of the laboratory reference frame. A first order function fit to the data was removed from each Z and Y data independently. This was performed to extract any monotonic drift of the WR during the ten second period.

As only the WR node compliance was studied in this research, only the steady state responses were analyzed. The compliance was estimated based on the relative displacement between the WR locations prior to the perturbation and after the perturbation. The relative displacement between these two steady state WR locations was calculated by computing the difference between two means of data points: one, called SS1, for the WR location prior to perturbation, and the other, called SS2, for the WR location after perturbation. Both means were computed on a series of data points which did not include the overshoot peaks. The steady state location SS1 was defined as the mean of 30 data points (.6 sec): 25 points before the command was issued to the Wrist Rocket (illustrated on Figure 6.5 as a vertical dotted line) plus 5 points after. The steady state location SS2 was defined as the mean of the last 61 data points (1.2 sec) of the 70 data points which followed the command issued to the Wrist Rocket. The results of this averaging technique applied on the data of Figure 6.7a, is shown in Figure 6.8. Every one of the six step responses of a sequence was treated with the same procedure. Data along Z were treated independently of data along Y.

Over the ten second period, the "change of state commands" to the Wrist Rocket were at: 1.5, 3, 4.5, 6, 7.5, and 9 seconds (cf. Figure 6.5). Based on the previous convention, the UP perturbations occurred at 1.5, 4.5 and 7.5 seconds, and the DOWN ones at 3, 6 and 9 seconds. A typical plot of the steady state WR relative displacements for one experimental condition is shown in Figure 6.9a. Each symbol represents the relative displacement following one step perturbation. Normally, there would be a total of 72 (6 perturbations x 12 perturbation sequences) symbols per plot. The relative displacements were normalized to an input force of 1N in all directions.
FIGURE 6.7 Comparison of WR motion along Z axis following a step perturbation sequence. Top plot (6.7a) is for the instruction "do not intervene", and the bottom plot (6.7b) is for the instruction "maintain the initial position of the hand prior to force perturbations". Vertical dotted bars represent the time of onset commands issued to the Wrist Rocket.
FIGURE 6.8 Results of the averaging technique used to compute the WR steady state location before and after perturbation. Solid plain and dashed horizontal lines represent the steady state locations respectively before and after perturbations. Data along Z axis, long stick, 50% force, subject 10.
FIGURE 6.9 Steady state relative displacements of the WR following a step force perturbation, for all sequences of one experimental condition. All data has been normalized to a 1N step force. 9a (Top plot): all relative displacements. 9b (Bottom plot): means of all relative displacements of a same perturbation sequence (anyone of the twelve possible). Y axis is a vertical displacement; Z axis is a horizontal displacement. Since top right cluster of data were not good, they are not plotted.
There is a given symbol associated to all steady state relative displacements that belong to the same perturbation sequence. Because of the limited number of symbols available in the graphics software, some of the them were reused to illustrate the relative displacements of different sequences. To avoid confusion, sequences with same symbols were chosen such that the displacements were clearly not in the same area on the plot. Same symbols were also used for relative displacements that were produced by force sequences that are similar i.e. 1 and 7, 2 and 11, 4 and 10, 5 and 8 (cf. Figure 6.4) For illustration purposes, UP relative displacements and inverted DOWN displacements were then averaged together, to produce only one relative displacement per force perturbation sequence. The results are shown in Figure 6.9b.

Our goal was to use the relative displacements and come up with an estimate of the compliance matrix \( C \) which relates the WR displacements to the input forces:

\[
\bar{X} = C \bar{F},
\]

i.e. in a more explicit form:

\[
\begin{bmatrix}
    x \\
    y \\
    z \\
    \theta \\
    \alpha \\
    \beta \\
\end{bmatrix} =
\begin{bmatrix}
    c_{xx} & c_{xy} & c_{xz} & c_{x\theta} & c_{x\alpha} & c_{x\beta} \\
    c_{yx} & c_{yy} & c_{yz} & c_{y\theta} & c_{y\alpha} & c_{y\beta} \\
    c_{zx} & c_{zy} & c_{zz} & c_{z\theta} & c_{z\alpha} & c_{z\beta} \\
    c_{\theta x} & c_{\theta y} & c_{\theta z} & c_{\theta \theta} & c_{\theta \alpha} & c_{\theta \beta} \\
    c_{\alpha x} & c_{\alpha y} & c_{\alpha z} & c_{\alpha \theta} & c_{\alpha \alpha} & c_{\alpha \beta} \\
    c_{\beta x} & c_{\beta y} & c_{\beta z} & c_{\beta \theta} & c_{\beta \alpha} & c_{\beta \beta} \\
\end{bmatrix}
\begin{bmatrix}
    f_x \\
    f_y \\
    f_z \\
    \tau_x \\
    \tau_y \\
    \tau_z \\
\end{bmatrix}
\]  \quad (6.2)

The displacement vector represents the motion of the WR node, and the force vector represents the force conditions that could be potentially produced at the WR node. The coordinate 6 represents the angle of rotation of the drill handle about its axis i.e. the \( X \) axis, \( \beta \) about the \( Y \) axis and \( \alpha \), about the \( Z \) axis.

The matrix can be estimated using common system identification techniques, by measuring the WR steady state displacements following force or torque perturbations produced by the Wrist Rocket. In our setup, the Wrist Rocket could only produce forces in the \( ZY \) plane since it was fixed along the drill axis. In addition, if we assume that \( x \) displacements were negligible, and since the angles \( \alpha \) and \( \beta \) are directly related to the displacements \( y \) and \( z \), the part of Equation 6.2 of interest is then:
\[
\begin{bmatrix}
  y \\
  z \\
  \theta
\end{bmatrix}
= 
\begin{bmatrix}
  c_{yy} & c_{yz} & c_{y\theta} \\
  c_{zy} & c_{zz} & c_{z\theta} \\
  c_{\theta y} & c_{\theta z} & c_{\theta \theta}
\end{bmatrix}
\begin{bmatrix}
  f_y \\
  f_z \\
  \tau_x
\end{bmatrix}.
\] (6.3)

This is the compliance which is responsible for the motion of the WR in the plane perpendicular to the stick axis, i.e. in the ZY plane, for perturbations in that plane. By design, the pneumatic perturbation device does not generate any moment about its axis, thus \( \tau_x = 0 \). In addition, since the rotation of the drill about its axis was not relevant in the stability analysis, it was not analyzed any further. The final compliance which was estimated was therefore:

\[
\begin{bmatrix}
  y \\
  z
\end{bmatrix}
= 
\begin{bmatrix}
  c_{yy} & c_{yz} \\
  c_{zy} & c_{zz}
\end{bmatrix}
\begin{bmatrix}
  f_y \\
  f_z
\end{bmatrix},
\] (6.4)

where,

\[
C_p = 
\begin{bmatrix}
  c_{yy} & c_{yz} \\
  c_{zy} & c_{zz}
\end{bmatrix}.
\] (6.5)

The last four coefficients of the submatrix were found by a trivariate regression of the displacements \( y \) and \( z \) on the input forces. Both regressions were performed independently with a normal least square technique which assumed no errors in the force inputs. The regression equations used were:

\[
y = c_{yy} f_y + c_{yz} f_z \] (6.6)

and

\[
z = c_{zy} f_y + c_{zz} f_z \] (6.7)

### 6.1.3 Statistics on stiffness eigenvalues

The \( C_p \) matrix, if symmetric, can be graphically represented by an ellipse in the ZY plane. If the matrix is not symmetric, a symmetric and anti-symmetric matrix can be obtained in the following way:

\[
C_{ps} = \frac{1}{2} (C_p + C_p^T) = 
\begin{bmatrix}
  u_{yy} & u_{yz} \\
  u_{zy} & u_{zz}
\end{bmatrix},
\] (6.8)

with \( u_{zy} = u_{yz} \).

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for the symmetric part, and the anti-symmetric is

$$C'_{pa} = \frac{1}{2}(C_p - C'_p) = \begin{bmatrix} v_{yy} & 0 \\ 0 & v_{zz} \end{bmatrix}.$$  \hspace{1cm} (6.9)

An ellipse can then be computed from the symmetric matrix $C'_{ps}$. This ellipse is perpendicular to the usual stiffness matrix measured in similar studies (Mussa-Ivaldi et al., 1985).

The precision of the symmetric matrix components can be estimated by application of the following error analysis. If

$$w = a(u + v),$$  \hspace{1cm} (6.10)

then the standard deviation of $w$ is:

$$s(w) = a \left[ s^2(u) + s^2(v) \right]^{\frac{1}{2}}.$$  \hspace{1cm} (6.11)

Using these last two equations, the precision on the symmetric compliance matrix components are easily obtained:

$$s(u_{yy}) = \frac{\sqrt{2}}{2} s(c_{yy})$$

$$s(u_{zz}) = \frac{\sqrt{2}}{2} s(c_{zz})$$

$$s(u_{yz}) = \frac{1}{2} \left[ s^2(c_{yz}) + s^2(c_{zy}) \right]^{\frac{1}{2}}.$$  \hspace{1cm} (6.12)

Eigenvalues of the symmetric matrix partly characterize the ellipse. For a 2x2 matrix, there is an explicit formulation for the compliance eigenvalues:

$$\lambda_{1,2} = \frac{1}{2} \left[ u_{yy} + u_{zz} \pm \sqrt{(u_{yy} + u_{zz})^2 - 4(u_{yy}u_{zz} - u_{yz}^2)} \right].$$  \hspace{1cm} (6.13)

Our goal is to obtain an estimate of the WR node stiffness matrix. It is preferable to describe the node properties using the stiffness matrix for two reasons:

1. the stability analysis of Chapter 2 was introduced with a stiffness concept, and
2. it will be easier to compare the results of this research with previous studies in motor control which described the hand mechanical properties with stiffness values.
Based on the previous developments on the compliance matrix, one can obtain the WR node stiffness matrix by:

\[ K = C^{-1}. \]  \hspace{1cm} (6.14)

As previously performed, the stiffness matrix can be decomposed into a symmetric matrix

\[ K_S = \frac{1}{2}(K + K^T) \]  \hspace{1cm} (6.15)

and an anti-symmetric matrix

\[ K_A = \frac{1}{2}(K - K^T). \]  \hspace{1cm} (6.16)

The components of the anti-symmetric matrix are called the curl (Hogan, 1985; Mussa-Ivaldi et al., 1985). If the WR node characteristic behaves as a passive system, one should expect this curl to be zero.

The symmetric matrix can be geometrically represented by an ellipse. The ellipse can be characterized partly by its eigenvalues which are computed from equation 6.13:

\[ \lambda_k = \frac{1}{\lambda}. \]  \hspace{1cm} (6.17)

The variation of the eigenvalues of the symmetric stiffness matrix with different pushing conditions were investigated in this research. Therefore, it was important to come up with some precision on their estimation.

Although eigenvalues are used in a wide range of applications in science, we found no studies which thoroughly investigated the problem of eigenvalue accuracy. Most of the studies were satisfied with finding a maximum bound, within which all eigenvalues of a matrix are contained. This technique is based on the Gerschgorin's theorem (Blum, 1972). This is too conservative a technique if statistical analysis must be performed on the variations of eigenvalues with pushing conditions. A comprehensive analysis of eigenvalue statistics is a significant project by itself. A quick solution was thus chosen: the linearization procedure. This technique is acceptable if higher order terms in the series expansion of equation 6.13 are not too large.

The Taylor series expansion of equation 6.13 is:
\[ \lambda_k(u_{yy}, u_{zz}, u_{yz}) = \lambda_0 + \sum_{i=1}^{n} \frac{1}{i!} \left[ \left( \frac{\partial}{\partial u_{yy}} + \frac{\partial}{\partial u_{zz}} + \frac{\partial}{\partial u_{yz}} \right) \lambda_k(u_{yy}, u_{zz}, u_{yz}) \right] \bigg|_{point \ 0} \]

or, explicitly:

\[ \lambda_k = \lambda_0 + \frac{\partial \lambda_k}{\partial u_{yy}} du_{yy} + \frac{\partial \lambda_k}{\partial u_{zz}} du_{zz} + \frac{\partial \lambda_k}{\partial u_{yz}} du_{yz} + \]

\[ \frac{1}{2} \frac{\partial^2 \lambda_k}{\partial u_{yy}^2} du_{yy} + \frac{1}{2} \frac{\partial^2 \lambda_k}{\partial u_{zz}^2} du_{zz} + \frac{1}{2} \frac{\partial^2 \lambda_k}{\partial u_{yz}^2} du_{yz} + \]

\[ du_{yy} \frac{\partial^2 \lambda_k}{\partial u_{yy} \partial u_{zz}} + du_{zz} \frac{\partial^2 \lambda_k}{\partial u_{yz} \partial u_{zz}} + du_{yz} \frac{\partial^2 \lambda_k}{\partial u_{yy} \partial u_{xz}} + \]

\( H.O.T. \)

with all derivatives evaluated at the reference point O.

If only the first order terms are kept, we are left with a linear model and using equation 6.10, the standard deviation on the eigenvalues simplifies to:

\[ s(\lambda_k) \approx \left[ \left( \frac{\partial \lambda_k}{\partial u_{yy}} \right)^2 s^2(u_{yy}) + \left( \frac{\partial \lambda_k}{\partial u_{zz}} \right)^2 s^2(u_{zz}) + \left( \frac{\partial \lambda_k}{\partial u_{yz}} \right)^2 s^2(u_{yz}) \right]^\frac{1}{2} \]

with all derivatives evaluated at the reference point O. These derivatives are straightforward to obtain, and they will not be included here.

Other parameters also characterize the symmetric stiffness matrix. For instance, the area of the ellipse is proportional to the product of the eigenvalues; the shape of the ellipse may be characterized by the ratio of the eigenvalues, and the orientation of the ellipse can be described by the angle between the main axis of the ellipse (i.e. the eigenvector associated with the largest eigenvalue) and the Z axis. The influence of the magnitude of static instability on WR node stiffness was investigated by analysing the variations of these ellipse characteristics.
6.2 RESULTS

6.2.1 Raw data plots

The easiest way to look at the perturbation data is to plot the steady state relative displacement vector of the WR, as well as the force input vector on the same plot. This can be done for all twelve perturbation sequences. The advantage of this plot is that very little processing is performed on the data. A typical plot is shown in Figure 6.10. The data are the same as in Figure 6.9. Circles represent the tip of the force vectors, and the stick lines represent the associated WR relative displacement vector in the ZY plane. Every displacement vector represents the mean of 6 measurements: 3 UP and 3 DOWN. The origin of the displacement vectors is set to the associated force vector tip.

Additional dashed stick lines are also plotted. They represent the relative displacements that would occur for each perturbation sequence, if the compliance field at the WR was represented by the computed symmetric compliance matrix \( C_{ps} \). The dashed stick lines provide a general appreciation of the goodness of fit of the \( C_{ps} \) matrix on the displacement data. Plots for all subjects and all conditions are given in Appendix F.

6.2.2 Normalized data plots

Plots, such as the one in Figure 6.10, are somewhat confusing since the force inputs did not have the same magnitude along every direction. In order to avoid the distortion introduced, it is preferable to look at the steady relative displacements normalized to a 1 N input force magnitude, such as those shown in Figure 6.9. The top plot gives the normalized relative displacements of all 6 relative displacements, for every perturbation sequence. The symbols represent the tip of the relative displacement vectors. An ellipse was fitted to the data using the symmetric compliance \( C_{ps} \) matrix. The bottom plot represents the average of the 6 relative displacement vectors for each perturbation sequence. The same ellipse is also represented.

The quality of fit of the trivariate regression used to obtain the compliance matrix can be assessed by analyzing the correlation coefficient presented in Tables 6.3 to 6.7. When any of the correlation coefficients were below .8, this particular data was discarded for future analysis. Some regression were very good, others much less. We believe that the bad cases were due to the difficulty of respecting the "do not intervene" paradigm in the presence of step forces of importance provided by the Wrist Rocket. Those cases are identified as "Bad data" in Table 6.2. There was not any logical choice to select .8 as a
limit other than trying to keep most of the data in the pool. It was also chosen based on
the normalized displacement plots. Data which had correlation coefficient lower than .8
did not have very good consistency in the displacements.

FIGURE 6.10 Raw displacement plots. Force inputs on the stick by the Wrist Rocket
(o), means of steady state relative displacements (---), relative displacements that would
be induced if the compliance matrix was \( C_{PS} \) (---). Notice that for the force data, the
scales should read in Newtons and not millimeters. Since top right cluster of data were
not good, they are not plotted.
<table>
<thead>
<tr>
<th>Subject 10</th>
<th>test 1</th>
<th>test 2</th>
<th>test 3</th>
<th>test 4</th>
<th>test 5</th>
<th>test 6</th>
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</tr>
</thead>
<tbody>
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<td>r*</td>
<td>0.89,89</td>
<td>0.71,79</td>
<td>0.91,96</td>
<td>0.87,91</td>
<td>0.92,93</td>
<td>0.85,89</td>
<td>0.82,86</td>
<td>-</td>
</tr>
<tr>
<td>axial force exerted (N)</td>
<td>68</td>
<td>116</td>
<td>68</td>
<td>116</td>
<td>68</td>
<td>116</td>
<td>68</td>
<td>-</td>
</tr>
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<td>max $\zeta_k$ (N/m)</td>
<td>4854</td>
<td>7927</td>
<td>1210</td>
<td>1414</td>
<td>1360</td>
<td>1488</td>
<td>2121</td>
<td>-</td>
</tr>
<tr>
<td>min $\zeta_k$ (N/m)</td>
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<td>1530</td>
<td>391</td>
<td>467</td>
<td>464</td>
<td>618</td>
<td>644</td>
<td>-</td>
</tr>
<tr>
<td>Kins (N/m)</td>
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<td>1278</td>
<td>214</td>
<td>365</td>
<td>214</td>
<td>365</td>
<td>365</td>
<td>-</td>
</tr>
<tr>
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<td>2713</td>
<td>100</td>
<td>147</td>
<td>130</td>
<td>175</td>
<td>374</td>
<td>-</td>
</tr>
<tr>
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<td>101</td>
<td>10</td>
<td>16</td>
<td>15</td>
<td>30</td>
<td>34</td>
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<tr>
<td>curl (N/m)</td>
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<td>590</td>
<td>5</td>
<td>4</td>
<td>64</td>
<td>59</td>
<td>247</td>
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<tr>
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<td>-2.7</td>
<td>-6.4</td>
<td>-1.7</td>
<td>16.3</td>
<td>-6.5</td>
<td>-</td>
</tr>
</tbody>
</table>

* : Correlation coefficients of equations 6.5 and 6.6.
# : Angle between main stiffness eigenvector and Z axis of the laboratory reference frame
° : Negative stiffness due to static instability

**TABLE 6.3** Compilation of all parameters used to characterize the WR node stiffness ellipses. Subject 10.

<table>
<thead>
<tr>
<th>Subject 11</th>
<th>test 1</th>
<th>test 2</th>
<th>test 3</th>
<th>test 4</th>
<th>test 5</th>
<th>test 6</th>
<th>test 7</th>
<th>test 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>r*</td>
<td>0.95,96</td>
<td>0.96,75</td>
<td>0.94,95</td>
<td>0.91,95</td>
<td>0.94,94</td>
<td>-</td>
<td>0.94,98</td>
<td>-</td>
</tr>
<tr>
<td>axial force exerted (N)</td>
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<td>119</td>
<td>91</td>
<td>119</td>
<td>91</td>
<td>-</td>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>max $\zeta_k$ (N/m)</td>
<td>490</td>
<td>801</td>
<td>1057</td>
<td>908</td>
<td>2394</td>
<td>-</td>
<td>2219</td>
<td>-</td>
</tr>
<tr>
<td>min $\zeta_k$ (N/m)</td>
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<td>324</td>
<td>291</td>
<td>319</td>
<td>706</td>
<td>-</td>
<td>695</td>
<td>-</td>
</tr>
<tr>
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<td>286</td>
<td>374</td>
<td>1003</td>
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<td>771</td>
<td>-</td>
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<tr>
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<td>120</td>
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<td>258</td>
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<td>155</td>
<td>-</td>
</tr>
<tr>
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<td>9</td>
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<td>22</td>
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<td>15</td>
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</tr>
<tr>
<td>curl (N/m)</td>
<td>52</td>
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<td>142</td>
<td>64</td>
<td>104</td>
<td>-</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>$\zeta_{max}^{\circ}$</td>
<td>1.5</td>
<td>2.5</td>
<td>3.6</td>
<td>2.8</td>
<td>3.4</td>
<td>-</td>
<td>3.2</td>
<td>-</td>
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<tr>
<td>$\alpha$ (deg)</td>
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<td>-15</td>
<td>-19</td>
<td>-15</td>
<td>-</td>
<td>-38</td>
<td>-</td>
</tr>
</tbody>
</table>

* : Correlation coefficients of equations 6.5 and 6.6.
# : Angle between main stiffness eigenvector and Z axis of the laboratory reference frame
° : Negative stiffness due to static instability

**TABLE 6.4** Compilation of all parameters used to characterize the WR node stiffness ellipses. Subject 11
<table>
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<th>test 3</th>
<th>test 4</th>
<th>test 5</th>
<th>test 6</th>
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<th>test 8</th>
</tr>
</thead>
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<tr>
<td><strong>r</strong></td>
<td>.96, .96</td>
<td>.92, .89</td>
<td>.96, .95</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>axial force exerted (N)</td>
<td>60</td>
<td>78</td>
<td>46</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>max $\lambda_{k}$ (N/m)</td>
<td>95</td>
<td>138</td>
<td>92</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>min $\lambda_{k}$ (N/m)</td>
<td>70</td>
<td>111</td>
<td>79</td>
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<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>$s(\lambda_{max})$ (N/m)</td>
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<td>curl (N/m)</td>
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<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\lambda_{max}/\lambda_{min}$</td>
<td>1.4</td>
<td>1.2</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\lambda_{max} \times \lambda_{min}$ ($\times 10^6$ N²/m²)</td>
<td>.007</td>
<td>.02</td>
<td>.008</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha$ (deg)#</td>
<td>16.5</td>
<td>22</td>
<td>11</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>

* : Correlation coefficients of equations 6.5 and 6.6.
# : Angle between main stiffness eigenvector and Z axis of the laboratory reference frame

**TABLE 6.5** Compilation of all parameters used to characterize the WR node stiffness ellipses. Subject 13

<table>
<thead>
<tr>
<th>Subject 14</th>
<th>test 1</th>
<th>test 2</th>
<th>test 3</th>
<th>test 4</th>
<th>test 5</th>
<th>test 6</th>
<th>test 7</th>
<th>test 8</th>
</tr>
</thead>
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<tr>
<td><strong>r</strong></td>
<td>.88, .88</td>
<td>-</td>
<td>-</td>
<td>.81, .62</td>
<td>.89, .86</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>axial force exerted (N)</td>
<td>78</td>
<td>-</td>
<td>-</td>
<td>116</td>
<td>46</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>max $\lambda_{k}$ (N/m)</td>
<td>1132</td>
<td>-</td>
<td>-</td>
<td>1829</td>
<td>940</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>min $\lambda_{k}$ (N/m)</td>
<td>449</td>
<td>-</td>
<td>-</td>
<td>1099</td>
<td>338</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kins (N/m)#</td>
<td>245</td>
<td>-</td>
<td>-</td>
<td>365</td>
<td>145</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$s(\lambda_{max})$ (N/m)</td>
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<td>-</td>
<td>-</td>
<td>290</td>
<td>118</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$s(\lambda_{min})$ (N/m)</td>
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<td>-</td>
<td>-</td>
<td>105</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>curl (N/m)</td>
<td>28</td>
<td>-</td>
<td>-</td>
<td>67</td>
<td>24</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\lambda_{max}/\lambda_{min}$</td>
<td>-</td>
<td>-</td>
<td>1.7</td>
<td>2.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\lambda_{max} \times \lambda_{min}$ ($\times 10^6$ N²/m²)</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>.3</td>
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<tr>
<td>$\alpha$ (deg)#</td>
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<td>-</td>
<td>-32</td>
<td>-35</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* : Correlation coefficients of equations 6.5 and 6.6.
# : Angle between main stiffness eigenvector and Z axis of the laboratory reference frame
# : Negative stiffness due to static instability

**TABLE 6.6** Compilation of all parameters used to characterize the WR node stiffness ellipses. Subject 14

Page 178
<table>
<thead>
<tr>
<th>Subject 15</th>
<th>test 1</th>
<th>test 2</th>
<th>test 3</th>
<th>test 4</th>
<th>test 5</th>
<th>test 6</th>
<th>test 7</th>
<th>test 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r^* )</td>
<td>-</td>
<td>-</td>
<td>82.86</td>
<td>.88,.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>axial force exerted (N)</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>78</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>max ( \lambda_j ) (N/m)</td>
<td>-</td>
<td>-</td>
<td>3062</td>
<td>894</td>
<td>-</td>
<td>-</td>
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<tr>
<td>min ( \lambda_j ) (N/m)</td>
<td>-</td>
<td>-</td>
<td>549</td>
<td>204</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kins (N/m(^\circ))</td>
<td>-</td>
<td>-</td>
<td>661</td>
<td>245</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>s( ( \lambda_{max} )) (N/m)</td>
<td>-</td>
<td>-</td>
<td>878</td>
<td>161</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>s( ( \lambda_{min} )) (N/m)</td>
<td>-</td>
<td>-</td>
<td>28</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>curl (N/m)</td>
<td>-</td>
<td>-</td>
<td>87</td>
<td>66</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \lambda_{max} ) ( \div ) ( \lambda_{min} )</td>
<td>-</td>
<td>-</td>
<td>5.6</td>
<td>4.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \lambda_{max} ) ( \times ) ( \lambda_{min} ) (( \times 10^6 ) N( ^2 )/m(^2 ))</td>
<td>-</td>
<td>-</td>
<td>1.7</td>
<td>.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \alpha ) (deg(^\circ))</td>
<td>-</td>
<td>-</td>
<td>-15</td>
<td>-5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* : Correlation coefficients of equations 6.5 and 6.6.
# : Angle between main stiffness eigenvector and Z axis of the laboratory reference frame
\( \circ \) : Negative stiffness due to static instability

**Table 6.7** Compilation of all parameters used to characterize the WR node stiffness ellipses. Subject 15.

The quality of fit of the compliance ellipse (and by extension the symmetric stiffness matrix) to the experimental data can be assessed visually. A quantitative evaluation can be provided by comparing the magnitude of the curl to the maximum stiffness eigenvalues. In general, the curl was lower than 15% of the maximum eigenvalue. This is in the range of ratios obtained by Mussa-Ivaldi et al. (1985). Such low curl corroborates the suggestion that human hand exhibits spring-like properties.

Several characteristics of the stiffness symmetric matrix \( K_s \) are compiled in Tables 6.3 to 6.7, for all subjects and all experimental conditions. The particular experimental conditions for each test are listed in Table 6.2. In general, subjects had to push on a medium length stick, a long stick, and a long stick with the drill handle centered on the stick. In addition, a few tests investigated the hand stiffness during a pulling situation. Because of the complexity of the apparatus used for this particular test, these results should be interpreted with care. The long metal wire used to oppose the axial force added significant dynamics to the system during perturbations. At most, the pulling test can provide some hint for the understanding of the relation of hand-stick node stiffness with axial force exerted and stick length.
The data of Tables 6.3 and 6.7 are better appreciated in a series of plots which show the variation of each of the parameters with axial force, for the four major experimental conditions tested. Figure 6.11 shows the results for the maximum eigenvalue of the stiffness symmetric matrix, Figure 6.12 for the minimum eigenvalue, Figure 6.13 for the ratio of the eigenvalues, Figure 6.14 for the area of the stiffness ellipse (product of the eigenvalues), and Figure 6.15 for the orientation of the main axis of the ellipse.

Error estimates (+/- one standard deviation) are provided for the maximum and minimum eigenvalues as vertical bar in Figures 6.11 and 6.12. When the vertical bars are not visible, it is because the errors are too small.

6.3 ANALYSIS AND DISCUSSION

The goal of this chapter was to investigate what particular hand stiffness that subjects used to push on the stick. Initially, we thought that we could compute this stiffness based on the measurement of the stiffness matrix apparent at the Wrist Rocket node. With the particular experimental setup that we used, this appeared to be impossible for the following two reasons:

1. we are facing an over determined problem
   
   This problem is better visualized if we assume a planar model of the system, as shown in Figure 6.16. The stiffness apparent at the Wrist Rocket node depends on the tangential stiffness $K_T$ and rotational stiffness $K_\theta$ of the hand. Since, a priori, we do not know what combination of stiffness subjects used, it becomes impossible to determine their magnitudes since the transverse forces at the tip of the stick were not measured.

2. the magnitude of static instability can not be accurately estimated

   Even if we knew at least the hand-stick node stiffness, it would still be difficult to exactly compute the hand stiffness because we do not have a good instability model of the subject-stick system.

Nevertheless, because the WR node stiffness depends only on the hand-stick node stiffness, we can still infer some conclusions on the variation of hand-stick node stiffness with level of axial force, stick length and handle location.
FIGURE 6.11 Variations of the maximum eigenvalue of the symmetric matrix $K_s$ with level of axial force exerted. Vertical bars represent the +/- standard deviation error. Data from subjects 11, 13 and 15. The "x" symbol, overlapped by a circle, on top right plot, represents the data of s10, pushing at location 2 height.
FIGURE 6.12 Variations of the minimum eigenvalue of the symmetric matrix $K_S$ with level of axial force exerted. Vertical bars represent the +/- standard deviation error. Data from subjects 11, 13 and 15. The "x" symbol, overlapped by a circle, on top right plot, represents the data of s10, pushing at location 2 height.
FIGURE 6.13 Variations of the ratio of the eigenvalues of the symmetric matrix $K_S$ with level of axial force exerted. Data from subjects 11, 13 and 15. The "x" symbol, overlapped by a circle, on top right plot, represents the data of s10, pushing at location 2 height.
FIGURE 6.14 Variations of the eigenvalue product of the symmetric matrix $K_S$ ellipse with level of axial force exerted. Data from subjects 11, 13 and 15. The "x" symbol, overlapped by a circle, on top right plot, represents the data of s10, pushing at location 2 height.
FIGURE 6.15 Variations of the orientation $\alpha$ of the maximum eigenvalue of the symmetric matrix $K_s$ with level of axial force exerted. Data from subjects 11, 13 and 15. The "x" symbol, overlapped by a circle, on top right plot, represents the data of $s_{10}$, pushing at location 2 height.
The first striking observation is the magnitude of the maximum stiffness eigenvalue, ranging from 2000 to 8000 N/m (cf. Figure 6.11), which is much higher than postural values measured by Mussa-Ivaldi et al. (1985), up to around 1200 N/m for a 10N force compensation at the hand. This difference is understandable since we measured the stiffness at the WR node, and not the hand. However, hand stiffness can be estimated from the hand-stick node stiffness by adding the absolute value of the negative stiffness $K_{ins}$ due to the static instability, as listed in Tables 6.3 to 6.7. In these tables, the stiffness $K_{ins}$ was estimated by assuming the simplest model treated in Chapter 2, i.e. an infinite length manipulator. Since the hand-stick node stiffness can not be exactly estimated from the WR node stiffness matrix (see previous discussion), a crude analysis was performed. If we assume that the effect of the hand is to provide an axisymmetric tangential stiffness field at the extremity of the stick (c.f. figure 6.16), we can then estimate the hand-stick node stiffness magnitude from the measurements of WR node stiffness. A simple analysis would show that the hand stiffness magnitude would be $0.74 K_R$ in the case of the Long stick, and $0.53 K_R$ for the Medium stick, where $K_R$ is the stiffness measured at the WR node. For subjects s11 and s15, this would indicate a hand-stick node stiffness of respectively 1200 and 1600 N/m, and 2575 N/m for s10. Two of these values are in the range of those obtained by Mussa-Ivaldi et al. (1985). Adding the stiffness due to instability, the hand stiffness becomes respectively 1895 and 2150 N/m for s11 and s15, and around 3739 N/m for s10. Such high values may come from the fact that, while
pushing on the handle, the rotational stiffness of the hand also contributes to the stabilization of the stick.

Other arguments also suggest that the hand rotational stiffness may be involved.
1. If we analyze the stiffness values obtained in the Long stick case, the WR node values are in the range of 1000 N/m, which leads to an estimate of hand-stick node stiffness of 740 N/m, and finally, adding the instability effect, to around 1000 N/m for the hand stiffness. This is about half of the Medium stick values. Either subjects selected lower hand stiffness when using the Long stick, or, as discussed in Chapter 2, the hand rotational stiffness becomes less effective for longer sticks, and therefore, does not contribute as much to the hand-stick node stiffness.
2. Stiffness values obtained in the Pulling situation are much lower i.e. in the 100 N/m range. Those values should be interpreted with care because the experimental setup that was used added significant dynamics to the response of the hand, due to its inertia and compliance. Nevertheless, a hand-stick node stiffness of 100 N/m is 10 times lower than the ones obtained when pushing. The difference may be due to the fact that the rotational stiffness of the hand can not contribute to the stabilization of the upper limb in the Pulling condition. Note that in this case, the negative stiffness due to instability would be as small as 50 to 100 N/m, if data from Figure 2.8 are used.

6.3.1 Is hand-stick node stiffness zero?

The research hypothesis stated that subjects would select a particular hand stiffness such that they would exactly compensate for the static instability of the stick. This implies that the apparent stiffness of the Wrist Rocket node should be zero for any level of axial force exerted. Values of the maximum and minimum eigenvalues of the stiffness symmetric matrices are generally over 500 N/m for all pushing conditions (cf. Figures 6.11 and 6.12). Five hundred Newtons/meter is in the range of postural stiffness values measured in the work of Mussa-Ivaldi et al. (1985). It is therefore clear that the research hypothesis is rejected.

6.3.2 Does hand-stick node stiffness remain constant, increase or decrease with axial force exerted?

Several studies investigated the variation of stiffness with force (e.g. Feldman, 1966; Rack et al., 1973, Hunter et al., 1982, McIntyre, 1990, Milner et al., 1992). The experiment performed by McIntyre (1990) is the closest to our experimental situation: subject hand stiffness was measured while they were asked to push or pull on a rope.
attached to a weight; axial forces of up to 30 N were investigated. All of these studies showed that stiffness increases with force. Therefore, in our experimental situation, as the static instability increases with axial force exerted, a given gain increase in hand stiffness may lead to either a decrease, an increase or a constant hand-stick node stiffness with axial force. A constant stiffness suggests that the hand stiffness gain would be exactly matched to the gain of instability with axial force. Subjects may prefer to set a constant non-zero stiffness such that there exists a given stability margin (McIntyre, 1990).

The results obtained in this present research suggest that both the maximum and minimum stiffness either remain constant or increase with axial force exerted. Because of the small number of subjects and experimental conditions, we were not able to statistically evaluate whether stiffness increases with force. In some subjects, stiffness increased with force, while in others, it remained constant. There is only one case (s11, Long stick) where the stiffness decreased. Further studies should be performed with additional force levels to clarify this point.

6.3.3 Does stick length influence hand-stick node stiffness?

If we carry back the WR node stiffness to the hand-stick node, using the crude analysis presented earlier, the ratio of hand-stick node stiffness (Medium/Long) should be $0.74/0.53$ i.e. 1.4. This is not the case when looking at Figures 6.11 and 6.12: the ratio is more in the range of 2.5. Hence, we conclude that stick length probably affects the hand-stick node stiffness. The reasons for higher stiffness in the Medium case may be an indication of the higher effectiveness of the rotational stiffness of the hand for shorter sticks (cf. Chapter 2).

Although results suggest that the hand-stick node stiffness magnitude may be affected, it is interesting to observe that orientation of the ellipse and ratio of stiffness eigenvalues are in the same range in the Medium and Long cases. Again, because of the small number of data points, no statistical analysis was performed to compare both cases. Invariance in shape and orientation would confirm the results obtained by Mussa-Ivaldi et al. (1985) which showed that subjects could voluntarily modify their hand stiffness magnitude, but appeared to be unable to change the orientation or the shape of the hand stiffness ellipses without modulation of the upper limb posture.
6.3.4 Does handle location matter?

One of the debatable questions in tool design is whether a drill handle should be aligned with the axis of the drill, or set off axis. Both designs are illustrated in Figure 6.17. Based on our experimental results, there is no clear trend in any of the five parameters between a long stick with a centered handle or an off axis handle. Future experiments should be pursued to clearly explain the effect of the handle by analyzing where the hand contacts the handle. This was not recorded during our experiments and it could be an important factor in the determination of the hand-stick node stiffness.

6.3.5 Does upper limb posture influence hand-stick node stiffness?

In order to force upper limb posture changes, the stick was set at location 2 height (cf. Chapter 5) instead of location 3. We were interested to see whether subjects would preserve the same hand-stick node stiffness for different heights. Only one subject had to do this test (s10, test 7). Results show that the maximum and minimum stiffness eigenvalues increased by as much as 50%. Consequently, the product of the eigenvalues also increased, and the ratio remained at about the same value. The orientation of the ellipse slightly changed, which may be expected because of the different upper limb posture. A higher WR node stiffness implies that a higher hand stiffness was used while pushing at location 2. The implication of this higher stiffness on the best drilling location is not very clear. If subjects had to increase their hand stiffness for some unknown reasons, drilling at location 2 would not be attractive. Additional studies should be pursued to clarify this topic.

6.4 CONCLUSIONS

The purpose of this experiment was to observe the hand stiffness that subjects use while pushing on a pivoting stick, and to determine if the observed patterns allow us to identify the control strategy selected in an interactive task with significant force production. Due to the small amount of experimental data and the lack of statistical analysis, the experiment was more suggestive than conclusive. The sample size of this experiment was low for several reasons:
FIGURE 6.17 Two designs of a drill: handle off axis, left, and handle centered with the drill axis, right.
1. limited number of subjects studied;
2. the long time period required to perform the experiments (4 hours for 7 tests),
3. the inconsistent responses of the subjects to step perturbations from the Wrist Rocket: a significant amount of data was discarded because of the bad fitting quality (any values with correlation coefficient below 8 were discarded).

Based on the five subjects that were investigated, results suggested that subjects did more than simply offset the static instability. The hand-stick node stiffness observed was in the range of 1600 N/m (maximum eigenvalue), which means a hand stiffness of about 2150 N/m. Analysis of the data tells us that:
1. subjects maintained either a constant or an increasing hand-stick node stiffness with axial force level,
2. hand-stick node stiffness appeared to be larger in the medium stick case, which might be due to the greater effectiveness of the rotational stiffness of the hand;
3. handle location, in relation to the stick axis, does not seem to influence the apparent hand-stick node stiffness; and
4. pushing height seems to affect the hand-stick node stiffness.

Two explanations might account for a stiffness increase with axial force. Subjects, for unknown reasons, may voluntarily select this strategy by tuning any one of the components of the neuromuscular system which make up the stiffness at the hand. There is also an alternative explanation for an increase in stiffness: it may just be a "side effect" of muscle activation. Evolution may have led to actuators that automatically stabilize themselves, because actuators without this property may have been less useful for survival. In this task, any automatic increase in stiffness must be larger than the increase of instability with axial force exerted on the stick. Future experiments should be performed to investigate if the increase in stiffness changes with the increase of instability. If the rate of hand stiffness increase is fixed, we would observe a distinctive trend of the hand-stick node stiffness.

Speculating, the static instability inherent in pushing on long objects may have been a driving force in shaping our neuro-musculo-skeletal system over the years. People suggest that the human brain superiority is what made them capable of using and making hand tools. There could also be a more physical explanation: some *homo sapiens* may
have had more adequate systems to properly use tools, hence improving their motor abilities with practice and eventually helping develop the brain to a superior level.

As far as tool design is concerned, it is still not clear whether a short drill or a long drill is more or less demanding physically since the only difference observed in this study may be explained by an increase in hand rotational stiffness efficiency. Subjects may just provide the same hand stiffness variation with level of force exerted, and the resulting stiffness of the hand-stick node varies in accordance to the geometry of the stick. However, hand-stick node stiffness is much stiffer in the direction of the handle axis, i.e. in the direction which facilitates the hand rotational stiffness action. Hence, since a handle is only efficient about an axis perpendicular to its axis, it would be appropriate to add some stabilizing devices which would help to the wrist stiffness in the direction of the handle axis. Such bracing already exists for canes.

For future experiments, we would suggest to use a different force perturbation device to improve the quality of hand response to perturbations. A ramp force excitation is probably more appropriate for this task because the step forces were somewhat drastic. Step force excitation also requires more data to estimate the compliance: in contrast, each point of a ramp force adds to the estimation of the compliance.
Chapter 7

Conclusions, contributions and future research

This thesis will conclude by first giving the highlights of the research. The major contributions will then be pointed out, along with the new research avenues that this work has opened up.

7.1 CONCLUSIONS

- This work has provided experimental data which tend to support the postulate that the kinematics of the limb is a significant factor in the drilling task:

1. posture is repeatable for kinematically and mechanically similar conditions;
2. there is no significant difference in upper limb posture for the range of axial forces and drill length investigated; and
3. the upper limb postures selected while drilling or while pushing on the drill when turned off were not statistically different.

- Results also suggests that a strategy of minimizing torques may be plausible. Right handed subjects generally aligned their shoulder with the drill axis to minimize shoulder torque, while left handed subjects aligned the drill axis with their elbow to minimize elbow torque. Further experiments with better techniques to measure joint locations should be conducted.
• The postural experiment has shown that humans do not seem to select upper limb posture to reach isotropy or maximum manipulability conditions, if a 2D planar model of the arm is assumed; this is in contrast to some of the concepts conveyed in the robotics field.

• The stability models have shown that pulling can be unstable in certain conditions and that the instability induced in pushing on a stick depends on several variables: the upper limb posture, the level and direction of axial force produced, the limb joints stiffness and the Jacobian of the stick.

• These models also showed that a handle can be useful in establishing the required stiffness at the stick extremity to maintain stability. However, stiffness experiments were not conclusive on this topic.

• The stiffness experiment has shown that subjects do not modulate their hand stiffness to exactly compensate for the static instability. Instead, stiffness appeared to increase, or at least remained constant with axial force exerted on the drill handle. A stiffness increase may just be a side effect of increase in muscle activation. However, to ensure stability, this "hardware tuned" increase in stiffness must be greater than the instability increase of the environment to ensure stability.

• The stiffness experiment suggests that hand stiffness is influenced by stick length: it is about twice higher in the medium stick case than in the long one. This increase may be due to the higher effectiveness of the hand rotational stiffness for shorter sticks. The very low stiffness measured in the pulling case also indicate that hand rotational stiffness may provide significant help to stabilize the stick.

7.2 CONTRIBUTIONS AND FUTURE RESEARCH

This research has been difficult to pursue because of the several unknowns involved: unknowns on the goal of the operator, unknowns on the hardware and control structure, unknowns on the particular experimental conditions to investigate, unknowns on the best experimental methods to use, or unknowns of the English language in the brain
of the author... Nevertheless, the entomologist has made its path through the wild forest: new species have been discovered and promising hunting spots have been identified.

The important contributions of the research are the following:

1. a thorough investigation of upper limb posture in a realistic task with a significant force production, showing that posture was invariant with force level and drill length;

2. a demonstration that isotropy characteristics or maximizing manipulability may not be the strategy that humans select when drilling, if we assume a 2D model analysis;

3. an extensive study of the stability of a manipulator in pushing or pulling showing that knowledge of the stiffness field apparent at the hand can provide substantial information about the stability characteristics of the manipulator;

4. indirect measurements of hand stiffness in a more realistic task, and in a plane different than the horizontal plane commonly studied in human motor control;

5. additional data suggesting that stiffness may increase with force produced, in a 3D task; and finally,

6. a theoretical demonstration that the tool handle may be important for the stability characteristics of the tool, as well as the physical demand from the operator.

Other secondary contributions, leading to future research topics were also made:

- A special method has been developed to quantify the upper limb posture based on the Grood&Suntay angles. This method should be refined using spherical regression techniques. In the course of developing the method, we have shown that the orientation of markers on a subject body are not important. What is important is to align the subject joint axes with the laboratory reference frame for the static file usually taken prior to the experiments.

- An extensive investigation of the quality of data provided by TRACK has been performed. Although the data quality was sufficient for this research, there exist some important problems which should be investigated further such as estimation of joint angles over a large range of motion.
• This research has provided a detailed analysis of the mechanics of pushing on a pivoting stick. Such analysis, to our knowledge, is not currently found in the literature. We have demonstrated that both wrist stiffness or shoulder stiffness can be used to stabilize a drill. We still do not know the relative contribution of each and further experiments should be undertaken to clarify this topic. The results would help in improving the design of tool handles.

• In the same vein, we have suggested a very simple model to estimate the potential pushing force that one can produce. This subject has been the object of several experiments which, apparently, have never provided a similar model. It is by analyzing this model that we observed that pushing should be better controlled when the feet are not close to each other. One of the foot should be moved anteriorly to the body and the other, posteriorly. If feet are kept together, the control of the force produced would become difficult because the person would create a non-minimum phase zero situation. For instance, a decrease in force production can only be achieved by increasing the force produced at first. I would strongly suggest to investigate the ability of controlling a force using different feet posture to verify this theory.

• This research is probably the first study to provide stiffness data in a plane perpendicular to the plane formed by the arm and the forearm. In addition, we suggested a linearization procedure to provide error estimates on the eigenvalues of a symmetric stiffness matrix. This is usually not addressed in other studies in the field. Further studies on the estimation of matrix eigenvalue errors should be conducted. This is a subject that appears not to have been addressed by statisticians.

• This study was initiated because of the interest of the author in the Hand-Arm Vibration Syndrome (HAVS). Our research provided important information on this subject: (1) the handle of power tools may influence the grip force required to implement a sufficient wrist stiffness to maintain stability; (2) hence, further experiments should be performed to investigate the variation of grip force with level of instability; (3) if hand stiffness is only a side effect of muscle activation, it seems unlikely that workers may be able to change their hand stiffness to reduce the transmission of tool vibrations to the hand.

• At the end of this research, I became interested in human evolution. I was particularly surprised by the fact that very rarely one asks himself why are we shaped that way?

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People in robotics have started the game by suggesting that human would try to select posture to achieve isotropy since the *homo sapiens* upper limb has interestingly the required brachial index. The importance of human evolution is clear because body shape is related to its environment. I would hence suggest to pursue some research to try to understand if our body was shaped based on some driving force of the nature. For instance, would we have the perfect upper limb structure to optimize the amount of energy that would be transferred to an object when hitting it with a stick of reasonable size?

- Finally, since the stiffness experiments contained a small number of subjects and experimental conditions, I would suggest to pursue the experiments to confirm the findings of this present research. A different perturbation apparatus should be used though, to improve the smoothness of the experiments and to increase the number of DOF of force perturbations. It would be most informative to find what is the gain increase of stiffness with force and test whether it is generally the same for different tasks.
REFERENCES


Bizzi, E. et al. - "Does the nervous system use equilibrium-point control to guide single and multiple joint movements?". - *Behavioral and Brain Sciences*, 15:603-613, 1992


Curodeau, Alain, Personnel communication, June 1993.


Ekenvall, L., Gemne, G., Tegner, R.- "Correspondence between neurological symptoms and outcome of quantitative sensory testing in the hand-arm vibration syndrome".- *British Journal of Industrial Medicine, 46*: 570-574, 1989.


Feldman, A.G.- "Functional tuning of nervous system with control of movement or maintenance of a steady posture ii. controllable parameters of the muscles iii. mechanigraphic analysis of the execution by man of the simplest motor task".- *Biophysics, 11*: 565-578, 766-775, 1966.

Flanders, M., Soechting, J.F.- "Arm Muscle Activation for Static forces in Three-Dimensional space".- *J. of Neurophysiology, 64*(6): 1818-1837.

Flash, T., Mussa-Ivaldi, F.- "Human arm stiffness characteristics during the maintenance of posture".- *Experimental Brain Research, 82*: 315-326, 1990.


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APPENDIX A

SELSOT/TRACK SYSTEM, A KINEMATICS MEASURING DEVICE

SELSOT/TRACK is an optoelectronic photogrammetric device that measures spatial kinematics of LED markers in 3D space. TRACK (for Telemetered Acquisition and Calculation of Kinematics Data) was designed at the Newman Laboratory at MIT. The system is based on two infrared SELSPOT II cameras that use lateral-photo-effect diodes to provide X and Y locations of markers projected on a 2D plane. Markers are LED's assembled in clusters of three so as to increase the total luminosity, by firing all three at the same time. In a standard marker, four sets of clusters are placed on a cross shaped Plexiglas plate to create a standard array, as shown on Figure A.1. Other marker shapes can be designed but at least three bundles are necessary to obtain 3D orientation information.

FIGURE A.1 Standard marker with 4 clusters of LEDs.
A marker is fixed at each location whose kinematics must be measured. The center of the marker is called the BCS (body coordinate system). The location of the BCS in space is obtained using stereophotogrammetric techniques. Since the relative positions of clusters of one marker are known, the marker orientation can also be computed in space. A quaternion based computation procedure, presented in section A.1, was used to compute the orientation of markers. The accuracy of the SELSPOT/TRACK system is studied in detail in section A.2. The system can easily support up to 8 standard markers and acquire data at a frequency of 200 Hz for each marker.

Camera kinematic data for each marker were stored in files with extension .raw. The data files were processed with TRACK (no smoothing was used) to produce data files with extension .qat. The .qat file format is given in the Table A.1. The data processing includes two error checking methods to eliminate bad data points due, for example, to reflections. These error checking methods are discussed by Mansfield (1990). The .qat files were stored on the SUN system or were transferred to a PC system for further analysis. The use of the quaternion method describing spatial body motion made easier the implementation of a software that computes the relative angles between two markers (this implementation was performed by Pat Lord and Michael Murphy, and was tested by the author of this thesis). The software is based on the work of Grood & Suntay (1983). The angles are computed in reference to a static file that must be taken prior to the experiments (the subject stands still with such a posture that the angles are nominally at zero degree reference).

The header, which is detailed in Table A.2, is contained in the file isi_struct.h. The remaining bytes contains kinematic data of each marker organized in a specific way. As an example, suppose that an experiment was performed with 2 standard markers, and data was taken at 50 Hz per marker for 1 sec. At each sampling moment, the location of a marker, in the laboratory reference frame, can be represented by 7 numbers which are: X, Y and Z coordinates of the BCS, and the 4 components of the quaternion related to this particular marker. A quaternion, as explained in section A.1, describes the spherical rotation of the marker coordinate system about its BCS, in the laboratory reference frame. Each marker has its own 7 float numbers for the 50 different frames of data that are recorded during the 1 sec experiment. These numbers are stored in the .qat file, after the header, in the following sequential way:
FORMAT OF .qat FILES

The kinematic data of each experiment were stored in .qat files after they were processed with TRACK. The format of these files is as followed:

<table>
<thead>
<tr>
<th>First 2048 bytes</th>
<th>file header that contains all characteristics related to the experiment (see next Table)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remaining bytes</td>
<td>kinematics data of markers</td>
</tr>
</tbody>
</table>

**TABLE A.1** General format of a .qat file

<table>
<thead>
<tr>
<th>FRAME #</th>
<th>data (all float format)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRAME 1</td>
<td>$X_1, Y_1, Z_1, q_1, q_2, q_3, q_4, X_2, Y_2, Z_2, q_1, q_2, q_3, q_4,$</td>
</tr>
<tr>
<td>FRAME 2</td>
<td>$X_1, Y_1, Z_1, q_1, q_2, q_3, q_4, X_2, Y_2, Z_2, q_1, q_2, q_3, q_4,$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>FRAME 50</td>
<td>$X_1, Y_1, Z_1, q_1, q_2, q_3, q_4, X_2, Y_2, Z_2, q_1, q_2, q_3, q_4,$</td>
</tr>
</tbody>
</table>

The accuracy and precision of TRACK are particularly important for the interpretation of experimental data. Therefore, the next two sections will describe first what quaternions are, and how they are used to express marker kinematics. The second section will describe the experiments that were conducted to figure out the precision of and validate the measuring system.
<table>
<thead>
<tr>
<th>Format</th>
<th>Variable name</th>
<th>Nb of bytes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>track_version [10]</td>
<td>10</td>
<td>Version of Track used</td>
</tr>
<tr>
<td>char</td>
<td>file_raw [10]</td>
<td>10</td>
<td>Name of original raw data</td>
</tr>
<tr>
<td>char</td>
<td>dir_raw [10]</td>
<td>10</td>
<td>Directory of original raw file</td>
</tr>
<tr>
<td>char</td>
<td>file_segm [10]</td>
<td>10</td>
<td>Segment file name</td>
</tr>
<tr>
<td>char</td>
<td>description [60]</td>
<td>60</td>
<td>Data description</td>
</tr>
<tr>
<td>char</td>
<td>samp_time [26]</td>
<td>26</td>
<td>Time of data sampling</td>
</tr>
<tr>
<td>char</td>
<td>calib_time [26]</td>
<td>26</td>
<td>Time of external calibration</td>
</tr>
<tr>
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<td>Raw data smoothing flag</td>
</tr>
<tr>
<td>char</td>
<td>smooth_3dp</td>
<td>1</td>
<td>3D data smoothing flag</td>
</tr>
<tr>
<td>char</td>
<td>smooth_bcs</td>
<td>1</td>
<td>BCS data smoothing flag</td>
</tr>
<tr>
<td>char</td>
<td>smooth_fpd</td>
<td>1</td>
<td>Force plate smoothing flag</td>
</tr>
<tr>
<td>char</td>
<td>interp_raw</td>
<td>1</td>
<td>Raw data interpolation flag</td>
</tr>
<tr>
<td>char</td>
<td>interp_3dp</td>
<td>1</td>
<td>3D data interpolation flag</td>
</tr>
<tr>
<td>char</td>
<td>interp_bcs</td>
<td>1</td>
<td>BCS data interpolation flag</td>
</tr>
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<td>char</td>
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<td>1</td>
<td>Processing window flag</td>
</tr>
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<td>bcsvelace</td>
<td>1</td>
<td>Compute bcs deriv's flag</td>
</tr>
<tr>
<td>char</td>
<td>only_3dp</td>
<td>1</td>
<td>Compute 3D data only flag</td>
</tr>
<tr>
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<td>null1</td>
<td>1</td>
<td>Use external calibration</td>
</tr>
<tr>
<td>char</td>
<td>selspot_flag</td>
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<td>Collect Selspot data flag</td>
</tr>
<tr>
<td>char</td>
<td>kistler_flag</td>
<td>1</td>
<td>Collect Kistler data flag</td>
</tr>
<tr>
<td>int</td>
<td>bad_points</td>
<td>2</td>
<td>Number of bad points found</td>
</tr>
<tr>
<td>int</td>
<td>nb_frames</td>
<td>2</td>
<td>Number of frames collected</td>
</tr>
<tr>
<td>int</td>
<td>nb_segment</td>
<td>2</td>
<td>Number of selspot segments</td>
</tr>
<tr>
<td>int</td>
<td>nb_channel</td>
<td>2</td>
<td>Number of selspot channels</td>
</tr>
<tr>
<td>int</td>
<td>act_frame1</td>
<td>2</td>
<td>Number of frames windowed</td>
</tr>
<tr>
<td>int</td>
<td>f_channels</td>
<td>2</td>
<td>Number of bad channels</td>
</tr>
<tr>
<td>int</td>
<td>f_segments</td>
<td>2</td>
<td>Number of bad segments</td>
</tr>
<tr>
<td>int</td>
<td>ray_badpt</td>
<td>2</td>
<td>Bad points due to skew ray</td>
</tr>
<tr>
<td>int</td>
<td>f_wframe</td>
<td>2</td>
<td>First frame of window</td>
</tr>
<tr>
<td>int</td>
<td>l_wframe</td>
<td>2</td>
<td>Last frame of window</td>
</tr>
<tr>
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</tr>
<tr>
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<td>Seg x-coord for each channel</td>
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<tr>
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<td>led_ycoord [32]</td>
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<td>Seg y-coord for each channel</td>
</tr>
<tr>
<td>float</td>
<td>led_zcoord [32]</td>
<td>128</td>
<td>Seg z-coord for each channel</td>
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<td>Explicit camera position vector</td>
</tr>
<tr>
<td>float</td>
<td>null3 [3][3]</td>
<td>24</td>
<td>Explicit camera rotation angles</td>
</tr>
<tr>
<td>float</td>
<td>ext_rotmtx [2][9]</td>
<td>72</td>
<td>Rotation matrix for ext calib</td>
</tr>
<tr>
<td>float</td>
<td>ext_trnvec [2][3]</td>
<td>24</td>
<td>Vectors for external calibration</td>
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<td>4</td>
<td>Focal length camera 1</td>
</tr>
<tr>
<td>float</td>
<td>focal_cam2</td>
<td>4</td>
<td>Focal length camera 2</td>
</tr>
<tr>
<td>float</td>
<td>max_ledvar</td>
<td>4</td>
<td>Max seen inter-led error</td>
</tr>
<tr>
<td>float</td>
<td>skewray_mx</td>
<td>4</td>
<td>Max seen skew ray error</td>
</tr>
<tr>
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<td>frequency</td>
<td>4</td>
<td>Frequency of collection</td>
</tr>
<tr>
<td>float</td>
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<td>4</td>
<td>Worst inter-LED length error</td>
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<tr>
<td>float</td>
<td>globx_axis</td>
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<td>Global origin relocation X</td>
</tr>
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</table>

**TABLE A.2** Header structure (as of June 1993)
<table>
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<th>glosx_axis</th>
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<th>Global origin relocation Y</th>
</tr>
</thead>
<tbody>
<tr>
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<td>glosz_axis</td>
<td>4</td>
<td>Global origin relocation Z</td>
</tr>
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<td>4</td>
<td>Forceplate X scale factor</td>
</tr>
<tr>
<td>float</td>
<td>fpxsc1</td>
<td>4</td>
<td>Forceplate Y scale factor</td>
</tr>
<tr>
<td>float</td>
<td>fpxsc1</td>
<td>4</td>
<td>Force plate Z scale factor</td>
</tr>
<tr>
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<td>fp zero [8]</td>
<td>32</td>
<td>Force plate zero offsets</td>
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<tr>
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<td>tdpcelace</td>
<td>4</td>
<td>Compute 3dp cell's flag</td>
</tr>
<tr>
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<td>direct</td>
<td>4</td>
<td>Direct orientation flag</td>
</tr>
<tr>
<td>float</td>
<td>creonics flag</td>
<td>4</td>
<td>Creonics flag</td>
</tr>
<tr>
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<td>mircam_mtx [2][9]</td>
<td>72</td>
<td>Neut mirror to camera mtx</td>
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<tr>
<td>float</td>
<td>mircam_vec [2][3]</td>
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<td>Neut mirror to camera vec</td>
</tr>
<tr>
<td>float</td>
<td>glmbir_mtx [2][9]</td>
<td>72</td>
<td>Global to neut mirror mtx</td>
</tr>
<tr>
<td>float</td>
<td>glmbir_vec [2][3]</td>
<td>24</td>
<td>Global to neut mirror vec</td>
</tr>
<tr>
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<td>mirror tilt [2]</td>
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<td>Mirror tilt angle</td>
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<tr>
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<td>quaternion</td>
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<td>Quaternion angle</td>
</tr>
</tbody>
</table>

**TABLE A.2** Header structure (as of June 1993) (continued and ended)

### A.1 QUATERNION AS A KINEMATICS COMPUTATION TOOL

In the eighteenth century Euler proved that:

"The general displacement of a rigid body with one point fixed is a rotation about an axis through the fixed point." (Stuelpnagel, 1964)

This suggests that a spherical rotation of a rigid body can be viewed as in Figure A 2, where an axis OL must be defined, as well as a rotation angle θ about this axis. Interestingly, this axis of rotation representation method requires only three parameters the orientation of the axis L (e.g. only two direction cosines are required) and the angle of rotation about the axis. With three parameters only, however, there is a 2-1 mapping since there are two distinct solutions to a finite rotation: they are about the same axis but the direction of the axis and the angle of rotation are in opposite directions. In practice, a four parameter representation is used to removed this ambiguity. In contrast, the usual 3x3 rotation matrices require nine parameters A rotation matrix has redundant information because it contains the rotation of each coordinate system axis
Anchored body

**FIGURE A.2** Rotation of a rigid body about an axis $L$ which passes through a point $O$.

Quaternions are commonly used in robotics to compute rotations of bodies in space using a four-parameter representation. Quaternions were developed in the mid nineteenth century when Hamilton got interested into defining the division law of two vectors (Rooney, 1978).

**A.1.1 What is a quaternion?**

Quaternions are sets of four numbers that can be used to represent, for example the four parameters of rotation of a rigid body. Quaternions are in the following form:

$$q = ai + bj + ck + d$$  \hspace{1cm} (A 1)

where $a$, $b$, $c$ and $d$ are real scalars and $i$, $j$, and $k$ are right vectors. A different representation of a quaternion is:

$$q = V_q + S_q$$  \hspace{1cm} (A 2)

where $V_q$ and $S_q$ are

$$V_q = ai + bj + ck$$

$$S_q = d$$  \hspace{1cm} (A 3)

Quaternions can then be either vectors or scalars if one of the previous components is zero. Finally a short representation of a quaternion is under a quadruplet form, i.e.,

$$q = (a, b, c, d)$$  \hspace{1cm} (A 4)

Some useful properties of the Quaternion algebra were used in this thesis. Given two quaternions $q_1$ and $q_2$,
\[ q_1 = a_1 \vec{i} + b_1 \vec{j} + c_1 \vec{k} + d_1, \tag{A.5} \]
\[ q_2 = a_2 \vec{i} + b_2 \vec{j} + c_2 \vec{k} + d_2, \]

the following operations were defined for quaternions:

**EQUALITY**
\[ q_1 = q_2 \tag{A.6} \]
\[ a_1 = a_2 \]
\[ b_1 = b_2 \]
\[ c_1 = c_2 \]
\[ d_1 = d_2 \tag{A.7} \]

**ADDITION**
\[ q_1 + q_2 = (a_1 + a_2) \vec{i} + (b_1 + b_2) \vec{j} + (c_1 + c_2) \vec{k} + (d_1 + d_2) \tag{A.8} \]

**SCALAR**
\[ \lambda q = \lambda a \vec{i} + \lambda b \vec{j} + \lambda c \vec{k} + \lambda d \tag{A.9} \]

**NEGATIVE**
\[ -q = (-1)q \tag{A.10} \]

**SUBTRACTION**
\[ q_1 - q_2 = q_1 + (-1)q_2 \tag{A.11} \]

**MULTIPLICATION**
\[ q_1 q_2 = (a_1 \vec{i} + b_1 \vec{j} + c_1 \vec{k} + d_1)(a_2 \vec{i} + b_2 \vec{j} + c_2 \vec{k} + d_2) \tag{A.12} \]
\[ q_1 q_2 = S q_1 S q_2 - V q_1 \cdot V q_2 + V q_1 \times V q_2 + \text{Scal} \tag{A.13} \]
\[ \text{and} \quad q_1 q_2 \neq q_2 q_1 \tag{A.14} \]

**CONJUGATE**
\[ K(q) = S_q - V_q \tag{A.15} \]
\[ K(q_1 + q_2 + \ldots + q_n) = K(q_1) + K(q_2) + \ldots + K(q_n) \tag{A.16} \]
\[ K(q_1 q_2 \ldots q_n) = K(q_1) K(q_2) \ldots K(q_n) \tag{A.17} \]

**NORM**
\[ N(q) = q K(q) = K(q) q = a^2 + b^2 + c^2 + d^2 \tag{A.18} \]

If the norm of a quaternion is equal to one, the quaternion is said to be a unit quaternion. Such a quaternion can be written as
\[ q = \cos \frac{\theta}{2} + e \sin \frac{\theta}{2} \quad (0 \leq \theta \leq \pi), \tag{A.19} \]
where \( e \) is given by
\[ e = \frac{a \vec{i} + b \vec{j} + c \vec{k}}{\sqrt{a^2 + b^2 + c^2}}, \tag{A.20} \]

known as a unit vector with its three direction cosines which define the quaternion axis. The angle \( \theta \) is the magnitude of rotation about the quaternion axis given by \( e \). On the basis of this notation, the unit quaternion components are more commonly written as the Euler parameters:
\[ a = l \sin \frac{\theta}{2} \]
\[ b = m \sin \frac{\theta}{2} \]
\[ c = n \sin \frac{\theta}{2} \]
\[ d = \cos \frac{\theta}{2} \]  \hspace{1cm} (A.21)

where \( l, m \) and \( n \) are the direction cosines. This is the quaternion form that will be used to compute spherical rotations. As the upper limb joint rotations commonly cross the 90 degree line, the form \((l, m, n, \theta)\) was not used because it has a singularity at 90 degree rotation, instead of 180 degrees. Further explanations can be found in Rooney (1978).

For a non zero \( q \), the reciprocal of the quaternion is defined as

\[ q^{-1} = \frac{K(q)}{N(q)}. \]  \hspace{1cm} (A.22)

This leads to

\[ qq^{-1} = 1 = q^{-1}q. \]  \hspace{1cm} (A.23)

Finally, we can show that

\[ (q_1q_2\ldots q_n)^{-1} = q_n^{-1}q_{n-1}^{-1}\ldots q_1^{-1}. \]  \hspace{1cm} (A.24)

These basic quaternion properties were used in this research to compute the kinematics of bodies in space.

A.1.2 Unit quaternion transformations

As mentioned previously, the quaternions with components given by A.21 can be used to represent spherical rotations of a rigid body in space. Two different types of rotations are of interest and are given by Rooney (1978).

Expressing rotations of a point in a fixed coordinate system

Given the initial position vector for the point is \( r_i \), the rotated position vector, defined in the same frame, will be:

\[ r_i(t_2) = qr_i(t_1)q^{-1}, \]  \hspace{1cm} (A.25)

where \( q \) is the unit quaternion that defines the rotation \( \theta \) of the vector about an axis. This rotation operation is equivalent to the usual form, using the rotation matrix \( R^\theta \).
\[ r_i(t_2) = R^\top r_i(t_1). \]  

(A.26)

**Expressing a coordinate transformation of a fixed point in space.**

Similarly, a coordinate transformation of a vector from one system to another is given by:

\[ r_2 = q^{-1} r_i q, \]  

(A.27)

where \( q \) is the quaternion that represents the rotation between the two coordinate systems. This rotation operation is equivalent to the usual matrix rotation form:

\[ r_2 = R r_i. \]  

(A.28)

The rotation matrix \( R \) is related to the components of A.21 in the following way (Rooney, 1978):

\[
R = \begin{bmatrix}
l^2(1 - \cos \theta) + \cos \theta & lm(1 - \cos \theta) + n \sin \theta & nl(1 - \cos \theta) + m \sin \theta \\
ml(1 - \cos \theta) - n \sin \theta & m^2(1 - \cos \theta) + \cos \theta & nn(1 - \cos \theta) + l \sin \theta \\
nl(1 - \cos \theta) + m \sin \theta & nm(1 - \cos \theta) - l \sin \theta & n^2(1 - \cos \theta) + \cos \theta
\end{bmatrix}
\]  

(A.29)

**Expressing the position vector of a point \( P \) fixed on a moving body**

Suppose a point \( P \), fixed to a moving coordinate system as shown on Figure A.3. The vector connecting the origin of this system to the point \( P \) is \( r_{ip} \), with components expressed in the fixed coordinate system. The problem is to express \( r_{0p} \), the location of \( P \) in the fixed coordinate system, knowing the position of point \( P \) in the moving coordinate system. Using A.27, it is easy to show that

\[ r_{ip} = q_{01}^{-1} r_p q_{01}, \]  

(A.30)

where \( r_p \) is the position of point \( P \) expressed in the moving coordinate system. Obviously, this vector must be known a priori to resolve the problem. Hence, the position of \( P \), expressed in the fixed coordinate system, is:

\[ r_{0p} = r_{01} + r_{ip}. \]  

(A.31)
Expressing the relative rotation between two rotated coordinate systems

The last computation of interest is to find the rotation matrix that passes from one system $S_J$, with a known orientation in a fixed reference frame $S_0$, to a system $S_2$, also with a known orientation in $S_0$. The rotation matrix can be represented by a relative quaternion that is found as following. Assume a vector $r_{po}$ from the origin of the fixed reference frame to a point $P$. Similar vectors $r_{p1}$ and $r_{p2}$ can also be defined from the origin of respectively the moving frames $S_J$ and $S_2$. Those vectors are defined in the fixed reference frame. Hence, equation A.27 gives the next relations:

$$r_{p1} = q_{01}^{-1}r_{po}q_{01}$$
$$r_{p2} = q_{02}^{-1}r_{po}q_{02}.$$  \[ (A.32) \]

By substitution, an expression relating both vectors $r_{p1}$ and $r_{p2}$ can be found:

$$r_{p2} = q_{02}^{-1}q_{01}r_{p1}q_{01}^{-1}q_{02}.$$  \[ (A.33) \]
Therefore, the quaternion that represents the relative rotation between the moving coordinate systems is:

\[ q_{12} = q_{01}^{-1} q_{02}. \]  \hspace{1cm} (A.34)

**FIGURE A.4** A point P defined in different coordinate systems.
A.1.3 How to compute the quaternion of a body coordinate system

Given a marker with \( n \) number of LED clusters located at known locations relative to the body coordinate system of the marker, the problem is to find the quaternion that represents the spherical rotation of the marker about the origin of the marker coordinate system, or alternatively, the rotation matrix. Shut (1961) suggested a method to describe the rotation matrix \( Q (R^T \text{ in A.26}) \) based on the components of the quaternion that represents the marker rotation in 3D space. This equation is indirectly given in A.29. For clarity, we can repeat the equation directly in terms of the quaternion components:

\[
R = \begin{bmatrix}
    d^2 + a^2 - b^2 - c^2 & 2ab - 2cd & 2ac + 2bd \\
    2ab + 2cd & d^2 - a^2 + b^2 - c^2 & 2hc - 2ad \\
    2ac - 2bd & 2hc + 2ad & d^2 - a^2 - b^2 + c^2 \\
\end{bmatrix} \cdot \frac{1}{d^2 + a^2 + b^2 + c^2} \quad (A.35)
\]

The quaternion components \((a,b,c,d)\) are found using the algorithm proposed by Shut (1961). He showed that each cluster provides two independent equations that relate the components. So, three or more non-collinear points on a marker can define at least one solution for \((a,b,c,d)\). The selected solution is obtained by performing a least-square estimation whose error function is based on the fact that we know, a priori, the nominal position of each cluster relative to the marker coordinate system. The technique is briefly explained by Mansfield (1990) and more details can be found in Shut (1961).

A.2 ACCURACY AND VALIDATION OF THE QUATERNION MEASURING SYSTEM

Computation of marker orientation (6 DOF) used to be performed with an Euler angle representation. A new algorithm was recently implemented in the last version of TRACK at the Newman Laboratory. This algorithm has not yet been extensively tested. This section will describe the experiments which were undertaken to determine the accuracy, the precision, and the validity of the kinematics that TRACK computes with the new algorithm.

A.2.1 Available data

An extensive number of tests were already performed by Mansfield (1990) to identify both, stochastic and systematic errors related to the measurement and computation of the position of the centroid of a triad, i.e. a cluster of LEDs. Results
showed that the standard deviation in the position of the centroid of light (CL) varied from .2 to .6 mm when the triad was located from 3 to 5 meters away from the camera. They also showed that the CL position of a triad varied by maximum .25mm around the geometrical centroid (GC), when the triad was rotated from 0 to 360 degrees about the axis passing through the GC, called the GC axis; finally, the CL was found to be located at 1 mm away from the plane of the triad, on the GC axis. Mansfield did additional tests to partially evaluate the validity of the algorithm, by measuring the position of 16 LED triads located on the calibration "tree" (calibration setup), illustrated in Figure A.5. His results showed that the external calibration was sensitive to objects that caused reflections in the cameras: variation of up to a "few" mm (he did not define what "a few" meant) were observed in the computed position of the cameras. Since the calibration tree is a large object with several LED clusters, he validated the position computation part of the algorithm over a large number of triads (clusters were disposed on the circumference of 2 concentric circles of 60 cm and 120 cm in diameter, with 8 clusters regularly distributed on each circle). He found measurement errors of up to 5 mm along the X axis, of up to 3 mm along the Y axis, and of up to 9 mm along the Z axis.

In a different study on knee kinematics, Murphy (1992) estimated the kinematic errors for the specific markers that he used: 8 clusters located on the circumference of a disk 80 mm in diameter. He fixed five markers on the leg of a human subject at rest (from the foot to the waist) and recorded data at 315 Hz for 2 seconds. He found standard errors of up to 5 mm in the CL computation. These are probably due in part, to body sway. The four quaternion components had standard errors of up to .003 for the vector components and .00001 for the scalar component. He also developed the equations for computing the standard errors of different quantities such as the distance between markers. Results showed that this error can be as high as 3 mm.

A.2.2 Proposed analysis

Even though extensive error estimation and validation experiments have been performed already by Mansfield and Murphy, further testing was needed for the following reasons:

1. The LED markers used in this research were different from those in previous experiments.
2. Above studies were done several years ago.
3. Some of these studies were not done with the quaternion algorithm.
FIGURE A.5 Special setup, named "calibration tree" for external calibration of the infrared cameras (Mansfield, 1990).
4. No investigations were done on the joint angle error estimation.
5. Some of the systematic errors measured were unacceptably high (9 mm along the Z axis).

The sources of errors that had to be addressed in our own investigation were multiple, the most important ones being:

- Internal calibration to correct non-linearity of the camera lens.
- External calibration to determine the coordinates of the focal point of each camera in the laboratory reference frame defined by the "calibration tree" coordinate system.
- The surrounding infrared light noise in the room.
- The manufacturing accuracy of the markers, i.e., their nominal shape and the estimated location of the centroids of each cluster.

These tests were used to get an estimate of the precision of the system, i.e. the standard deviation or standard error associated to the measurement.

Validity tests were also performed to get estimates of the accuracy of the measuring system:

1. Computation of distance between markers rigidly fixed at a given distance on a rigid body, for different orientations of the body in space.
2. Computation of joint angles using markers fixed on two rigid bodies in relative motion.
3. Estimation of a point P, based on the knowledge of the position and orientation of a coordinate frame in which P is defined.

Accuracy and precision are two different characteristics of a measuring device. An accurate measuring system is a system that gives a true value of a measurement.
A.2.3 Experiments

A.2.3.1 Error source analysis
For these tests, three standard markers were used such as those described earlier in this Appendix. They were fixed on a mechanical elbow with one DOF, as shown in Figure A.6. The "forearm" could be rotated as far as 120 degrees from the horizontal plane.

![Diagram of mechanical elbow with markers](image)

**FIGURE A.6** The mechanical elbow used for the experiments, fixed on a table top.

Internal Calibration errors
The internal calibration procedure is described in Mansfield (1990). This procedure is very long (3 hours per camera) and it is expected that the lens non-linearity of the cameras do not change over time. The non-linearity maps provided by Mansfield show that corrections of up to 20 camera units must be added to the data (this can mean up to 5 mm for the particular location of the viewing volume used in the tests). For our own purposes, we have used the maps already created by Mansfield (1990). The internal calibration does not necessarily correct the data perfectly, introducing systematic errors in the data. The magnitude of these errors can be estimated by checking the existence of trends in the data, for the various conditions of the experiments performed with the elbow. This will be discussed in the validation experiments described later.
External Calibration errors

The external calibration was performed by recording data of a vertically oriented planar structure, called the "calibration tree" (Cf. Figure A.5), that supports 16 LED clusters located at equal distance on the circumference of two concentric circles, of diameters equal to 60 and 120 cm. The tree was rotated about the Y axis of the laboratory reference frame, i.e. the vertical axis, at 6 different angles varying from about -45 to +45 degrees. By rotating the plane, a calibration object of spherical shape is created; it covers most of the camera range of view.

A complete external calibration procedure takes only about one minute. We estimated the error from this calibration procedure by performing it five times, and by comparing (1) the location and orientation of the cameras that each calibration provided and (2), the location of two of the three markers of the elbow after each calibration. The elbow was positioned at a specific location on the calibration tree (Cf. Figure A.5) so that it could be repositioned at the same place after each test. After each calibration, data was recorded at 200 Hz for a period of 5 seconds, to provide 1000 measurements per marker. Table A.3 summarizes the results of the external calibrations of TRACK. Both camera locations and orientations are given. Results show standard errors of up to 3 mm in the localization of the cameras and small variations in the rotation matrix components. These produced standard errors of 2 to 3 mm in the location of the two markers from trial to trial.

Despite these low precisions, the distance between two markers of the elbow was computed after each calibration, and a standard error as low as 1 mm was found. This is a better precision than the localization of markers alone, because distance is a relative measurement, and motion of both cameras as a rigid body would not affect its precision.

Surrounding noise errors

Data taken in the previous experiments can be used to estimate the surrounding noise of infrared rays that comes from sunlight, laboratory lights and reflections from surrounding objects. Marker #1 kinematic data, from one trial of the experiments performed for the external calibration error estimation, can be used to estimate the surrounding noise. Standard errors of X, Y and Z coordinates, and quaternion components are listed in Table A.4.
<table>
<thead>
<tr>
<th>CAMERA 1</th>
<th>average (m)</th>
<th>standard error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1.5263</td>
<td>0.002</td>
</tr>
<tr>
<td>Y</td>
<td>6393</td>
<td>0.003</td>
</tr>
<tr>
<td>Z</td>
<td>-3.4276</td>
<td>0.001</td>
</tr>
<tr>
<td>rotation matrix</td>
<td>.9071 .0753 - .4141</td>
<td>.002 .0001 .0004</td>
</tr>
<tr>
<td></td>
<td>.0075 .9808 .1948</td>
<td>.0003 .0001 .0007</td>
</tr>
<tr>
<td></td>
<td>.4248 -1798 8892</td>
<td>.009 .008 .0001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAMERA 2</th>
<th>average</th>
<th>standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (m)</td>
<td>1.5238</td>
<td>0.001</td>
</tr>
<tr>
<td>Y (m)</td>
<td>6509</td>
<td>0.003</td>
</tr>
<tr>
<td>Z (m)</td>
<td>-3.4555</td>
<td>0.001</td>
</tr>
<tr>
<td>rotation matrix</td>
<td>.9343 -.0674 .3500</td>
<td>.0007 .0004 .0002</td>
</tr>
<tr>
<td></td>
<td>-.0029 9805 .1967</td>
<td>.0003 .0002 .0008</td>
</tr>
<tr>
<td></td>
<td>-.3564 -1848 .9159</td>
<td>.0002 .002 .0005</td>
</tr>
</tbody>
</table>

**TABLE A.3** Camera locations and orientations computed after each external calibration

<table>
<thead>
<tr>
<th></th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Z (m)</th>
<th>q1</th>
<th>q2</th>
<th>q3</th>
<th>q4</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>-0.0173</td>
<td>-0.0680</td>
<td>-0.2461</td>
<td>0.0228</td>
<td>-0.0043</td>
<td>0.7113</td>
<td>7.025</td>
</tr>
<tr>
<td>standard error</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.0044</td>
<td>0.0048</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

**TABLE A.4** Average and standard errors of marker #1 kinematics (X,Y,Z values in meters).
The significance of the standard errors of the quaternion components is based on the definition of the quaternion. From section A.1, the quaternion components are defined as:

\[
q_1 = \cos(\frac{\alpha}{2})\sin(\frac{\theta}{2}) \\
q_2 = \cos(\frac{\beta}{2})\sin(\frac{\theta}{2}) \\
q_3 = \cos(\frac{\gamma}{2})\sin(\frac{\theta}{2}) \\
q_4 = \cos(\frac{\theta}{2})
\]

(A.36)

where \(\cos(\alpha)\), \(\cos(\beta)\) and \(\cos(\gamma)\) are the direction cosines of a rotation axis, and \(\theta\) is the rotation angle of the marker about this axis. We can translate the standard errors of the quaternion components into standard errors of the angles defining the axis of rotation, and the angle of rotation about the axis — since this transformation is not linear, these estimates should be taken with care. Using calculus of errors (Barford, 1985), it can be shown that:

\[
S(\theta) = \frac{2S(q_4)}{\sin(\frac{\theta}{2})}
\]

(A.37)

where \(S\) is the "standard errors" of the given variable. Similarly, we can obtain the standard errors for all three other angles if \(S(\theta)\) and \(S(q)\) are known:

\[
S(q_1) = \left[\left(-\frac{1}{2}\sin(\frac{\theta}{2})\sin(\frac{\theta}{2})\right)^2 S(\alpha)^2 + \left[\frac{1}{2}\cos(\frac{\theta}{2})\cos(\frac{\theta}{2})\right]^2 S(\theta)^2\right]^{\frac{1}{2}};
\]

\[
S(q_2) = \left[\left(-\frac{1}{2}\sin(\frac{\theta}{2})\sin(\frac{\theta}{2})\right)^2 S(\beta)^2 + \left[\frac{1}{2}\cos(\frac{\theta}{2})\cos(\frac{\theta}{2})\right]^2 S(\theta)^2\right]^{\frac{1}{2}};
\]

\[
S(q_3) = \left[\left(-\frac{1}{2}\sin(\frac{\theta}{2})\sin(\frac{\theta}{2})\right)^2 S(\gamma)^2 + \left[\frac{1}{2}\cos(\frac{\theta}{2})\cos(\frac{\theta}{2})\right]^2 S(\theta)^2\right]^{\frac{1}{2}};
\]

(A.38)

With the particular values of Table A.4, the following values of the standard errors are obtained:
<table>
<thead>
<tr>
<th>S(θ)</th>
<th>.161</th>
</tr>
</thead>
<tbody>
<tr>
<td>S(α)</td>
<td>.7088</td>
</tr>
<tr>
<td>S(β)</td>
<td>.7729</td>
</tr>
<tr>
<td>S(γ)</td>
<td>.8012</td>
</tr>
</tbody>
</table>

**TABLE A.5** Standard error for each angle.

Markers manufacturing accuracy

Manufacturing of markers was done with a milling machine. Accuracy in the placement of the LED was therefore not an issue. However, the LED diameter used in making the markers is in the order of .4 mm, and the half-power solid angle is 60 degrees (Murphy, 1992). TRACK commonly gave maximum inter-LED errors of around 2 to 3% of 4 inches. These errors are the maximum errors found in the computed distance between any of the four clusters to another, for one marker. Studies by Mansfield (1990) provided the required data for the estimation of these errors and no further experiments were performed.

A.2.3.2 Validation and accuracy of measurements

Validation of certain quantities measured with TRACK was necessary to evaluate the systematic errors that could have been introduced in the data. Validation was performed in four different ways.

1. Computation of distance between two markers rigidly connected, in different orientations about the Y axis of the laboratory reference frame:
   One standard marker and one plate marker (4 clusters located on the borders of a rectangular plate 8" x 7") were rigidly fixed on a rolling cart at a distance of about .406 m from each other. The cart was given three different orientations about the Y axis of the laboratory reference frame (Cf. Figure A.7). For each orientation, the distance between the two markers was computed. The results are shown in Figure A.8.
FIGURE A.7 Top view of both markers fixed on a cart, set at a certain angle from the vertical plane parallel to the cameras.

FIGURE A.8 Distance between two markers for various orientations relative to the cameras.
The variation is about 1 mm, for a range of +35 degrees of rotation about the Y axis. This represents a small .3% error, indicating that the non-linear maps and external calibration were very accurate. The standard error on distance can be estimated based on .0003 standard errors on X, Y and Z measurements. Calculations lead to a .42mm standard error, which is consistent with the results obtained in this test.

2. **Computation of the mechanical elbow flexion angle**

Joint angles are an important aspect of this research. Therefore, particular attention was given to estimate the standard error in flexion angle estimation. The mechanical elbow was again used for this estimation. The elbow was oriented more or less parallel to the cameras, seating flat on a table top which lies in the XZ plane of the laboratory reference frame (Cf. Figure A.9). All three markers were affixed on the forearm as shown in Figure A.5. Shims of different thicknesses were added under the forearm extremity to raise it, and induce angular rotation of the forearm from 0 to close to 90 degrees. Marker locations were then recorded at 200 Hz for .25 sec, and then processed with the quaternion algorithm of **TRACK 5.1**. Several trials were realized with different forearm rotations. The same set of tests was performed for two more orientations of the mechanical elbow on the table top: for a positive 32 degree rotation about the Y axis of the laboratory reference frame, and for a -25 degree rotation about the same axis. The flexion angle was calculated in several ways and the results are shown in Figure A.10. The methods used to compute the angles were the following:

1. Manual measurement of marker 2 height, relative to the zero angle position, and use of trigonometry to obtain the flexion angle. Although these data also have errors associated with them (standard deviation of about 1 degree on angle estimation), they were used as a reference to the Grood & Suntay method.

2. Flexion angle computed with the fourth quaternion component of markers 1 and 2 for the elbow in the zero orientation condition. In this particular situation, the elbow was actually rotated at 7 degrees about the Y axis and the fourth quaternion of both markers 1 and 2 (since they are rigidly fixed on the forearm) can provide a good estimate of the flexion angle. Since the elbow is not exactly at zero angle orientation, we should expect some bias in the data, in comparison with other estimation methods. This estimation method should provide slightly lower values than what they are in reality.
FIGURE A.9 Top view of the setup to measure the rotation of the mechanical elbow standing on a table top in front of the infrared cameras.

FIGURE A.10 Errors in computing elbow flexion angle using different techniques.
3. Using the Grood & Suntay algorithm (based on quaternion kinematics computation), angles of flexion were computed for each orientation of the elbow system relative to the cameras. The angle is defined as the flexion angle between markers #2 and #3.

All angle values are within a range of 5 degrees from each other, with the zero orientation and positive orientation close to each other (within 2 degrees) but the negative orientation with slightly higher angles (4 degrees) over most of the range from 0 to 90 degrees. The Grood & Suntay method seems adequate to compute joint angles with an accuracy that we could estimate as 5 degrees over the entire viewing range of the cameras. The Grood & Suntay method produced values which were in the same range as values obtained by other estimation techniques.

Because of the high inaccuracies involved in the preceding tests, additional tests were performed with the elbow fixed at around 35 degree angle, and the elbow was moved at different orientations relative to the cameras. The Grood & Suntay method produced flexion angle values which varied within a range of 5 degrees. Therefore, Grood & Suntay method can provide accurate values only within a limited range of view of the cameras.

3. Computation of distance between markers #1 and #2, and #1 and #3

The distances between markers 1 and 2, and between 1 and 3, were also computed from the data obtained in the elbow flexion angle estimation study. Results are shown in Figure A.11.

As the markers #1 and #3, and #1 and #2 are rigidly fixed to the elbow system, we should expect a similar distance for all flexion angles. Figure A.11 does show that the distances vary by about 2 mm for results of a given orientation of the mechanical elbow about the Y axis. If all results are combined, the distance accuracy increases to 10 mm from 0 to 90 degree rotation of the elbow. Results from the arm are worse than the forearm, because marker #1 was fixed on the pivot section that is connected to the forearm. As the marker may not have been perfectly aligned with the hinge axis, a rotation of the elbow would systematically change the distance between the arm markers.
There seems to exist some offsets for different orientations of the elbow about the $Y$ axis; that is probably due to the non-linearity maps. The apparently sinusoidal variation of the forearm distance probably comes from inappropriate corrections from the non-linearity maps. This information could eventually be used to improve TRACK accuracy.

**FIGURE A.11** Comparison of inter marker distances. From marker #1 to #2, for the forearm, and from marker #1 to #3, for the arm. Symbol "o" is for the situation where the mechanical elbow is parallel to the plane facing the cameras i.e. in the XY plane. Symbol "+" is for the mechanical elbow rotated by 32 degrees about the Y axis. Symbol "-" is for mechanical elbow rotated by -25 degrees about the Y axis.
4. Drill tip estimation location: for estimation of a point P at a fixed distance from a marker.

Parts of the analysis in this research required to estimate the location of a given point P, located at a known fixed distance from the origin of the local coordinate system of a marker. For example, the drill tip location was estimated using the information from the marker that is located close to the handle, since the two points are rigidly fixed to the drill. Estimation of the standard error of the location of a remote point P was done by asking a subject to locate the tip of the drill at a given point P on a vertical oriented board, and to position the drill at different handle orientations from trial to trial. The various drill orientations that the subject used can be expressed using the quaternion components of the marker fixed on the drill. They are given in Table A.6.

A physical interpretation of the quaternion components can be found in this Appendix. For instance, in the first test, the drill was mainly rotated about the Z axis with a positive angle. Estimations of the drill tip location, relative to the laboratory reference frame are given in Table A.7.

The location of the drill, for each test, is illustrated in Figures A.12 and A.13 where three points of the drill (tip, 90 degree angle point and grasping location on the handle) are connected together to illustrate a pseudo drill in the XY and ZX planes respectively. Results show that the drill tip precision is about 2 mm, for the X and Y axes, and 3 mm for the Z axis. These results agree with those of the mechanical elbow experiment.
<table>
<thead>
<tr>
<th>TRIAL</th>
<th>q1</th>
<th>q2</th>
<th>q3</th>
<th>q4</th>
</tr>
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<tbody>
<tr>
<td>test 1</td>
<td>-0.0215</td>
<td>0.0219</td>
<td>0.0080</td>
<td>0.9995</td>
</tr>
<tr>
<td>test 2</td>
<td>-0.0077</td>
<td>0.0198</td>
<td>0.0083</td>
<td>0.9997</td>
</tr>
<tr>
<td>test 3</td>
<td>-0.0173</td>
<td>0.0394</td>
<td>0.0075</td>
<td>0.9990</td>
</tr>
<tr>
<td>test 4</td>
<td>0.0269</td>
<td>0.0446</td>
<td>0.0234</td>
<td>0.9984</td>
</tr>
<tr>
<td>test 5</td>
<td>-0.0093</td>
<td>0.0418</td>
<td>0.0260</td>
<td>0.9987</td>
</tr>
<tr>
<td>test 6</td>
<td>0.0015</td>
<td>0.0191</td>
<td>0.1026</td>
<td>0.9945</td>
</tr>
<tr>
<td>test 7</td>
<td>-0.0011</td>
<td>0.0426</td>
<td>-0.2072</td>
<td>0.9774</td>
</tr>
<tr>
<td>test 8</td>
<td>-0.0159</td>
<td>0.1830</td>
<td>0.0246</td>
<td>0.9827</td>
</tr>
<tr>
<td>test 9</td>
<td>0.0002</td>
<td>-0.1328</td>
<td>0.0244</td>
<td>0.9908</td>
</tr>
<tr>
<td>test 10</td>
<td>0.2664</td>
<td>0.0370</td>
<td>0.0299</td>
<td>0.9627</td>
</tr>
<tr>
<td>test 11</td>
<td>-0.1400</td>
<td>0.0388</td>
<td>0.0260</td>
<td>0.9891</td>
</tr>
</tbody>
</table>

**TABLE A.6** Quaternions of the drill marker for each drill tip estimation test.

<table>
<thead>
<tr>
<th>Tip Location</th>
<th>X(m)</th>
<th>Y(m)</th>
<th>Z(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>test 1</td>
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<td>0.9849</td>
<td>-0.4420</td>
</tr>
<tr>
<td>test 2</td>
<td>-0.1464</td>
<td>0.9869</td>
<td>-0.4402</td>
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<td>test 3</td>
<td>-0.1460</td>
<td>0.9863</td>
<td>-0.4412</td>
</tr>
<tr>
<td>test 4</td>
<td>-0.1467</td>
<td>0.9866</td>
<td>-0.4405</td>
</tr>
<tr>
<td>test 5</td>
<td>-0.1468</td>
<td>0.9868</td>
<td>-0.4409</td>
</tr>
<tr>
<td>test 6</td>
<td>-0.1480</td>
<td>0.9873</td>
<td>-0.4409</td>
</tr>
<tr>
<td>test 7</td>
<td>-0.1429</td>
<td>0.9876</td>
<td>-0.4413</td>
</tr>
<tr>
<td>test 8</td>
<td>-0.1471</td>
<td>0.9861</td>
<td>-0.4474</td>
</tr>
<tr>
<td>test 9</td>
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<td>0.0033</td>
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**TABLE A.7** Estimation of drill tip location for each test.
FIGURE A.12 Drill location in XY plane, for each trial.

FIGURE A.13 Drill location in the ZX plane, for each trial.
A.2.4 Summary

Results of these experiments were not much different than those reported by Manfield (1990) and Murphy (1992). In general, the standard error in the position of one triad is about .5 mm based on Mansfield. For a 4 triads cross like marker, the BCS precision (or standard error) obtained in this study was also .5 mm. Given that the theoretical resolution of the cameras is 1/4096, i.e., .25 mm for a 1 meter diameter range of view, the results demonstrate the quality of the multiple triad marker concept to increase the resolution of the body coordinate system computation. Similarly, the precision on the computed distance between two markers was around .5 mm. However, the accuracy in computing a distance between two markers over the viewing range of the cameras is 5 mm. This high inaccuracy is probably due to the imperfection in corrections from the non-linearity maps.

Errors on the quaternion components lead to variation of about 1 degree for the angle of the direction cosines of the rotation axis. Based on these errors, the computation of a point P, fixed in a moving coordinate system for which the quaternion components are known, should have a precision of up to 3 mm. The results of this present study confirmed this theoretical estimation. Finally, due to the incorrectness of the non-linear maps, the Grood & Suntay algorithm produced joint angle inaccuracies of up to 5 degrees. However, if the object remains in a limited space of the range of view (+/- 10 cm), the accuracy would be more in the range of 2 degrees.
APPENDIX B

HARDWARE DESCRIPTION AND SPECIFICATIONS

B.1 COMPUTER ARCHITECTURE

In order to obtain the kinematics and posture of the upper limb, to perform data acquisition, and to control the Wrist Rocket in real-time, we used a VME-bus based system because of its high speed real-time capabilities. The diagram in Figure B.1 illustrates the layout of the different components installed on the VME-bus expansion board.

![Diagram of VMEbus expansion and connections to outside systems]

FIGURE B.1 VMEbus expansion and connections to outside systems

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The main processor of the system is a SUN 3/160 workstation. The VME-bus expansion is connected to this workstation via a MVME repeater 2000 that ensures transfer of information within 40 nanoseconds. To the far left of the expansion, there are three MVME microprocessor boards (MVME133-1 (AA), MVME133 (B), MVME133-1 (AB)). Each board contains a MC68020 processor running at 16.67 MHz (for the MVME133-1) and 12.5 MHz (for the MVME133), a floating point coprocessor MC68881, a programmable timer clock MC68901 MFP that can initiate internal board interrupts, and 1 Mbytes of RAM. Each board can respond to any of the seven interrupts level lines, but are usually manually jumped such that they respond to specific levels. Compiled software is transferred to any of the MVME133 boards through the expansion bus using the program "startup" written by Pat Lord of the Newman Laboratory at MIT. The compiled programs are loaded at address 10000 of the RAM of the MVME133. The real-time software designed on the SUN are compiled by the program "mce" written by Pat Lord. The software that controls the SELSPOT cameras (TRACK) for Telemetered Acquisition and Calculation of Kinematic Data) is loaded on both the MVME133AA and B. The software for A/D and D/A control (Tradda7) is loaded on the MVME133 AB. Tradda7 is synchronized with TRACK by monitoring the trigger signal (blue button) of the SELSPOT system on channel 0 of the A/D board. Both programs are therefore synchronized within a few microseconds.

The 12 bit A/D board (DVME 612B) records signals from the force cell and Wrist Rocket command signals from the D/A board for synchronization purposes. The board has a 160000 Hz throughput and an input impedance of 10 Mohm. The D/A board (DVME 628) provides the control signals to the Wrist Rocket. It has a settling time of 6 µsec and a 12 bit accuracy.

The programmable timer A (MC68901) of the MVME133-1 AB is used to initiate an A/D conversion sequence, at a predetermined rate, by producing a local interrupt on the MVME133-1 board AB. Savings of data from the A/D board is performed by an interrupt handler responding to a level 3 interrupt initiated by the A/D board each time a conversion is finished. The interrupt handler runs on board AB and therefore, is part of the Tradda7 software. The data is stored in the RAM of the MVME133-1 AB board. The D/A conversion is performed in the level 3 interrupt handler of the MVME133-1 AB board.
Tests were performed on the VMEbus to evaluate the capabilities of the real-time execution of A/D and D/A and TRACK.

D/A limitations (alone):

The test consisted of running a small software loop (located on the MVME133-1 board) that repeatedly wrote to the D/A board. The fastest frequency at which the D/A could be run was 38460 Hz. That limitation is probably due to the MVME133-1 CPU speed limitation since the VMEbus and the D/A board specifications are much faster.

A/D limitations (alone):

For this test, we used the interrupt command mode to operate the A/D board. The inboard timer A of the MVME133-1 AB board was used to clock the acquisition rate. The maximum frequency at which we could sample depends on the number of channels used to acquire data. Figure B.2 illustrates the frequency dependent limitation. Again, this limitation is probably due to the speed limitations of the CPU of the MVME133-1 board.

D/A and A/D limitations (together):

The addition of D/A operation to the A/D program reduced the bandwidth of the system by 80 Hz, for a sixteen channel acquisition (i.e. down to 1971 Hz) and by about 200 Hz, for an eight channel acquisition (i.e. down to 3892 Hz). Both A/D and D/A programs should be run on independent boards to know whether the decrease comes from a VMEbus limitation or from the CPU limitations.

D/A, A/D and TRACK limitations (together):

As a final test, A/D, D/A and TRACK (300 Hz with 12 channels) were run at the same time. Both for eight and sixteen channels of acquisition, there was a decrease in A/D performance by 400 Hz, compared to A/D operation alone. An eight channel acquisition was now limited to 3490 Hz and a 16 channels acquisition was limited to 1571 Hz. Obviously, the VMEbus affects the bandwidth limitation of the real-time program in this case. A possible solution to improve the speed of the real-time operation is to switch the A/D acquisition command mode from interrupt driven, to manual mode by the MVME133-1 board. Indeed, the arbiter of the MASTER (the MVM#133-1 AA) can handle so much interrupts that are initiated from the A/D board and the TRACK board. Since the present limitations were not significant for our experiments, the A/D was used in the interrupt command mode.
FIGURE B.2 Bandwith limitation of the A/D board versus number of channels read.

B.2 THE ROLLING CART

Since the SELSPOT cameras could not be moved easily, a rolling cart was built in order to provide a pseudo wall on which subjects could use the drill. The cart is illustrated in Figure B.3. The cart was positioned at an angle such that all the markers used to instrument the subject were in the SELSPOT camera field of view. The cart wheels were then locked to avoid motion while the subject was pushing on the cart with the drill. A pseudo wall (4 feet by 2 feet) was made out of two inch thick K2 panel. The panel was attached to two rods at the top. The rods were supported by six linear bearings, fixed to the top of the cart, to allow the panel to slide with little friction. The panel was allowed to slide until it hit a rod that was rigidly attached to the six axes force transducer described in section B.3. The axial force that was exerted on the drill was then transmitted through this rod to the force cell. It is clear that the measurement of axial force was not of high accuracy because: (1) the force cell would not measure any transverse force transmitted from the drill to the panel; and (2), deflections of the panel, which varied with drilling location, would produce slightly different force distribution between the rods and the force cell due to friction in the bearings. A complete discussion on the subject can be found in section 5.1.2.
FIGURE B.3  Rolling cart for drilling experiments.
B.3 FORCE CELL APPARATUS AND RELATED ELECTRONICS

The axial force exerted on the drill by the subjects was monitored with a force transducer located behind the vertical board. The force measuring device used was a Barry & Wright 6 axis force transducer, model FS6-120A. It is a 12 bit digital force transducer sampling at 480 Hz. A third order analog low pass filter, with cutoff at 120 Hz, was built in to avoid aliasing. Additional digital filtering was also performed with a second-order programmable digital filter, with roll off set at 60 Hz. The output force signal was obtained by setting the force cell in analog output format. The signal was recorded by the A/D system located on the VME-bus system. A sampling frequency of 200 Hz was used.

The axial force that subjects exerted on the drill was fed back to the subjects using an LED digital display. A visual signal was used instead of an audio signal because the latter was not appropriate for experiments that use the force perturbation device which was very noisy. Five LEDs were attached at the middle of the metal drilling panel, such that the subject could easily see them while drilling. The task was to maintain the first three LEDs on. Each LED represented a different force level. From LED 2 to 3, there was about a 10 N increase, and between LED 3 and 4 there was as well a 10 N increase. The electronic schematics of the LED digitizer is illustrated in Figure B.4.

B.4 THE MAKITA POWER DRILL

The drill selected for this research was a Makita, model #6510LVR 3.5A. The total weight of the drill is 1.48 Kg (section B contains the motor and the gear train). A sketch of the drill is shown in Figure B.5, with relevant dimensions. The drill was instrumented with an LED marker in order to compute the locations of points D1, D2 and D3 in the laboratory reference frame. Validation experiments, given in Appendix A, have shown that the standard deviation, in the estimation of the location of point D1, was about 2 mm. Points D2 and D3 had lower standard deviation values. The locations of all three points in reference to the LED marker are given in Table B.1, for all three drill bit lengths. These points were measured on the drill by installing the drill on a milling machine. The drill was easily dismantled in two sections (A and B) and section A was kept to perform the stick experiments described in Chapter 6.
FIGURE B.4 LED digitizer electronic schematics.
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<td>.038</td>
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</tbody>
</table>

**TABLE B.1** Reference points on the drill. Data in meters.

**FIGURE B.5** Makita power drill dimensions.
B.5 LED MARKERS FOR ARM POSTURE MEASUREMENTS

Up to six LED markers were fixed at different locations on the upper limb of the subjects, to measure the kinematics of body segments during the experiments. All markers were made with infrared LEDs (Litronix LD 242-3 IR emitter). Four out of the six markers were standard cross shape markers as shown in Figure A.1. The last two, used to monitor elbow and shoulder locations, had similar LEDs on a cross shape structure that was half the size of the other four markers: the length of the line segment between opposing clusters was 2 in. instead of 4 in. for the larger ones. Markers were fixed to the following locations, shown in Figure B.6:

![Diagram of LED markers on the body](image)

**FIGURE B.6** Locations of LED markers on subjects.

1. **drill**: One large marker was rigidly fixed on the drill. The position of any point P on the drill can be easily computed if its relative position is known in the marker local reference frame. The marker local coordinate system axes are shown in Figure B.6.

2. **forearm**: One large marker was fixed on the forearm. Spray glue (Spray sticken, Sitck-UM, Worth Cie: obtained at City Sports) was first put on the forearm. Prewrapped bandage (spongy like bandage) was then rolled around the forearm, and rubber elastic bands were finally wrapped around the forearm (Nylatex bands,
Chattanooga Corp.). Velcro bands were put at the back of the marker such that it was easy to fix it on the elastic band. Velcro straps were then used to firmly attach the marker to the forearm. This technique was used to minimize slipping due to subject sweating during the experiments. Skin motion does affect the motion of the marker but we assumed that it always produced the same offsets for identical upper limb postures. The forearm marker was used to compute the joint angles.

3. **elbow**: A small marker was fixed to the lateral side of the elbow, using the same technique as the forearm marker. Estimated measurements of the joint axis location was taken in reference to the marker local coordinate system. This marker was used to obtain an estimate of the elbow rotation axis for plotting purposes, and to provide additional data for repeatability analysis of upper limb posture.

4. **arm**: One large marker was fixed on the arm using the same technique as the forearm markers. This marker was used to compute elbow and shoulder joint angles.

5. **shoulder**: A small marker, fixed to a special mounting plastic structure was fixed on the top of the shoulder. The plastic structure was attached to a Velcro patch that was taped to the skin over the shoulder. Velcro straps, wrapped around the torso and the arm, were used to firmly attach the marker to the shoulder. This marker was used to obtain an estimate of the shoulder rotation axis for plotting purposes, and to provide additional data for repeatability analysis of upper limb posture.

6. **C7 vertebra**: A last large marker was used to monitor the motion of the torso in relation to the upper limb. It was particularly difficult to design an attachment system in this situation. A special plastic back plate was taped to the skin (with a sticky Velcro) over the C7 vertebra area. This area is the one that has the least skin motion and disturbances due to the motion of the scapula. The back plate was attached to a cotton collar that was wrapped around the neck of the subject, using just enough tension to secure it without being uncomfortable. A special rod system was also used to firmly compress the back plate to the back of the subject. The design is sketched on Figure B.6. A neoprene elastic band (TRU-FIT bought at City Sports) was first attached around the waist of the subject. Then, a light metal box was attach to the superior part of the band with a Velcro (the inferior part was used to attach the LCU SELSPOT boxes to the subject). A vertically oriented light weight graphite rod was connected to the metal box with a spherical joint. The top extremity of the rod was
firmly attached to the back plate (using a Velcro strapped) in the C7 region. Finally, an elastic cotton band was wrapped around the subject torso in order to compress the rod on the back. From the plastic back plate, a metal wire was fixed and shaped in such a way that the last marker, attached to the extremity of the wire, would stand over the shoulder, away from the subject face. Due to the wire compliance, vibration of the marker was significant. However, since data were taken in a nearly static posture, and 100 samples were taken and averaged, the vibrations were assumed to have negligible effect on the data accuracy. The marker coordinate system was oriented as shown in Figure B.6.
B.6 EXPERIMENTAL PROTOCOL SHEET FOR DRILLING TASK

| Date: __________________ | Subject: __________________ |

**STATIC TESTS**

| Horizontal 1: _______ | Vertical 1: _______ |
| Horizontal 2: _______ | Vertical 2: _______ |

**FORCE LEVEL TEST**

Maximum voltage on 200 N limit:
- 85% limit setting: N
- 65% limit setting: N
- 45% limit setting: N

**WOOD DRILLING**

| test 1: _______ | test 6: _______ |
| test 2: _______ | test 7: _______ |
| test 3: _______ | test 8: _______ |
| test 4: _______ | test 9: _______ |
| test 5: _______ | test 10: _______ |

**LOCATION TESTS:**

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**DRILL LENGTH TESTS**

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**DRILL OFF TESTS**

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APPENDIX C

THE WRIST ROCKET

The Wrist Rocket is a pneumatic force perturbation device that was designed by Edward Colgate (1985) (Cf. Figure C.2). It is an air jet system that can produce thrusts as high as 4N along three orthogonal axes. Each axis has two air nozzles, one directed in the positive direction of the axis, and the other in the negative direction. The air flow in each direction is controlled by a piston (1 per axis) which divides the air flow of each axis (Cf. Figure C.1). The piston is actuated in one direction by a 1000 psi hydraulic source. In the other direction, the oil pressure is removed and a stack of Belville springs generated a restoring force. The pistons and the nozzles are rigidly fixed to a plastic cuff. Most of the Wrist Rocket components were custom made to keep the device small and light (1 Kg). Only four tubes connect the Wrist Rocket to outside systems: 1 pneumatic line (1/4" OD, nylon) to provide 115 psi compressed air, and 3 hydraulic lines (1/8" OD, nylon) to control the position of the pistons which slides into custom made aluminum cylinder valves.

Each nozzle was originally equipped with strain gages to measure the thrust produced. Because of design problems, the strain gage systems provided inadequate data (see section C.2). Therefore, the thrust produced was not measured in real-time but off-line, and the consistency of the thrust over time was tested. The Wrist Rocket was originally designed to allow the production of any patterns of force perturbation by controlling the position of the pistons with a servovalve system supervised by a computer.

Unfortunately, because of the presence of friction and air mechanical interaction, we have been unsuccessful at positioning the pistons stably at any location in the cylinder. At present, the most reliable operation is to move the piston from one end to another, at maximum speed. This produces step force perturbations which will be discussed in the next section.
Figure C.1  Wrist Rocket X axis piston assembly.
FIGURE C.2 The Wrist Rocket installed on a drill handle. Servo-valves and hydraulic source (1000 psi) located on the cart, in the background.
C.1 DYNAMIC CHARACTERISTICS OF THE WRIST ROCKET

The purpose of the device was originally to measure the hand mechanical driving point compliance while a subject is accomplishing a given task. This is possible by wrapping the Wrist Rocket around the wrist of a subject and by applying a series of force perturbations in different directions. The kinematic response of the hand is then measured with a motion analysis system. Identification techniques may then be used to characterize the mechanical compliance apparent at the hand. At present, the Wrist Rocket can only produce step perturbations. Experiments were conducted to identify the dynamic characteristics of the Wrist Rocket to step commands, and to find out its physical limitations i.e. time delays, rise time, bandwidth and maximum thrust along each axis.

In order to characterize the Wrist Rocket, it was rigidly mounted on a 6 axis force cell. Further analysis showed that with this mounting procedure, the Wrist Rocket assembly would vibrate at a frequency close to 36 Hz, which would mask the step response of the thrust. In an attempt to increase the frequency of these unwanted vibrations, a special setup was designed as shown in Figure C.3. The Wrist Rocket was mounted on a rod supported at one extremity by a spherical joint, and at the other extremity by a simple contact between the sharp rod extremity and a small hole in the surface of the force cell end plate. This system had a natural frequency of about 71 Hz, away from the frequency range of interest (i.e. < 30 Hz).

Only the X and Y axes were tested since the Z axis was not used during the experiments. Both axes were tested by sending a square wave input to the servo-valves at a frequency of about 1 Hz for a period of 10 seconds. The resultant thrust from each axis was measured with the axis force cell. The signals were first analog filtered (Butterworth low pass, 3rd order, cutoff at 120 Hz) and then sampled at 480 Hz. The force cell gave an output voltage proportional to the force that the Wrist Rocket produced, at a 240 Hz rate. This signal was sampled by an A/D board at a frequency of 500 Hz. Characteristics of each axis was first studied separately, and then together.
FIGURE C.3 Experimental setup for Wrist Rocket calibration.
Figure C.4 shows a series of step responses for each axis. All steps from the same 10 seconds period were divided in segments based on the command signal, and then overlapped. Results show that the responses look generally repeatable for both axes (see Table C.1 for quantitative analysis). Because the piston is not actuated by oil pressure on one side, the dynamic response differs between oil pressure or spring driven curves. However, there is only about 5 msec difference between the time delays of both conditions. The high level of random noise at steady state is attributed to turbulence in the air flow, as well as vibrations from the mechanical parts of the measuring system. The step response in both axes exhibits some oscillations which are most likely due to the vibrations of the fixation system. The impulse mechanical response of the system was measured by hitting the Wrist Rocket, once installed on the force cell, and the dominant frequency of the response was in the range of the thrust oscillations observed in Figure C.4 (i.e. ~ 71 Hz). The high overshoot in axis X is attributed to the mechanical impact of the piston on the mechanical stop at the end of the cylinder. Several arguments support this affirmation:

- the impact of the piston on the mechanical stop is distinctively audible in the case of the X axis, "much" less in the Y axis which does not exhibit any overshoot.

- the highest overshoot is observed when the thrust changes from low to high. This is when the piston is oil pressure driven, i.e. when the effort source on the piston is greater. Table C.1 shows that oil pressure driven motion has a shorter rise time than spring driven motion;

- force measurements were taken during step inputs without the air flowing in the system and force levels of up to .6 N were observed, i.e. in the same range as the overshoot observed in the X thrust.
FIGURE C.4 Series of 4 step responses for axis X (A) and axis Y (B). Two oil pressure driven responses, two sprint driven responses. All responses were overlapped to show the repeatability of the dynamic response. Square wave solid line is the command signal to the servovalves.
If the previous assumptions are true, it would mean that the step response of the Wrist Rocket would have a much lower overshoot, and probably a faster settling time than what the data says, for the X axis under oil pressure force input. Figure C.4 contains four trials that were overlapped. Table C.1 describes the dynamic characteristics of nine of these step responses for each case i.e. 9 oil pressure driven, 9 spring driven for each axis. The mean responses are illustrated in Figure C.5 and C.6. The time rise of each axis is around 12 msec, either for oil pressure driven or spring driven condition. This would suggest a bandwidth of around 85 Hz! However, the rise time was computed without including the significant time delay that exists for each axis. If the delay is due to a high stiction of the piston instead of line effect delays in the oil line, then it should be included in the rise time. In that case, the rise time is in the order of 40-50 msec, suggesting a bandwidth of 20-25 Hz.

As a matter of fact, if a square wave input, of variable frequency, is sent to the servo valves, we can observe that the thrust will stop switching from high to low (X axis) or low to high (Y axis) in the frequency range 20-25 Hz. This behavior is shown in Figure C.7. At high frequency, both the X and Y axes will always "freeze" on a specific side. It is difficult, however, to predict on which side a piston is going to stick, based only on data from Table C.1, because dynamic characteristics seem similar.

With two axes (X and Y), the Wrist Rocket can provide four different static force vectors but up to twelve different changes of force vectors by different combinations of X and Y step inputs, i.e. with reference to Figure C.8, from position 1 to 2, from 1 to 3, from 1 to 4, from 2 to 1 etc. up to 4 to 3. If the orientation and the magnitude of the force vectors for each position and for each combination is plotted on a graph of X force versus Y force, we obtain Figure C.9, where each circle represents the tip of each force vector. The force magnitudes were obtained by computing the means of the 700 first points of the 800 that preceded the change of force vector. The variability of the cluster for each position is described in Table C.2, using convention from Figure C.8. Clearly, the Y axis is weaker in the positive direction, due most likely to the pressure drop in the air tubing to get to the nozzle: it is very long and it has one mechanical fitting. The general behavior of Figure C.9 was tested over a period of three days, without any significant changes.
<table>
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**TABLE C.1** Some dynamic characteristics of X and Y thrusts, for each of a 9 step sequence. $T_e$: time delay (time from command signal to the time where the response is outside the noisy band); $T_r$: rise time; (time from when the response leaves the noisy band to the time it reaches the steady state value; $T_d$: period of oscillation (time between two peaks of oscillation of the step response). Values are in milliseconds.
FIGURE C.5 X axis step responses. Graphs on first row are for scattered plots (left: oil pressure driven, right: spring driven). Graphs on second row are the same plots with solid lines. Bottom plot is the mean of both responses which were overlapped for comparison purposes: dashed line is motion from low to high (spring driven).
FIGURE C.6 Y axis step responses. First row graphs are scattered plots (left: oil pressure driven; right: spring driven). Second row graphs are same plots with solid lines. Last row plot is both responses overlapped for comparison purposes; dashed line is from high to low (spring driven).
FIGURE C.7 Step responses due to a square wave input at variable frequency. Top: X axis, Bottom: Y axis. The input frequency slowly increased from 3 to 6 seconds, to reach a maximum, and it was reduced back again. Divide by 70.62 to obtain Newtons.
FIGURE C.8 Schematic of the four force vectors of the Wrist Rocket.

FIGURE C.9 Locus of force vectors of the Wrist Rocket. Symbol "o" represents the tip of the force vector. Several trials were performed to show the variability.
<table>
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**TABLE C.2** Means and standard deviations of every static force vectors, referring to Figure C.9.

**C.2 FUTURE IMPROVEMENTS TO THE WRIST ROCKET DESIGN**

The Wrist Rocket has existed for a few years now and several people have tried to model the system to find out how to improve its frequency response, and how to provide proportional control on the position of the piston to allow variable force production along each axis (i.e. more than a simple square wave). Studies on the hydraulic part of the system have shown that nonlinear control of the oil pressure to the piston can help to the control of pistons. However, pneumatic analysis of the piston has shown that the compressed air flowing through the cylinder has a significant mechanical interaction with the spool, making the spool motion unstable in the midregion of its path. Current results show that the air dynamics are quite fast but the main problems lie in the motion of mechanical parts. Possible future improvements to the device are numerous:

- The Belville springs appeared to produce a lot of friction on the spool. They should be replaced by a different spring system or by a second hydraulic system.

- High vacuum grease was used to help decrease the friction but it has a high viscosity that actually adds a lot of damping to the system.
• In the case of a spring solution, the stiffness and length of the spring must be optimized based on experimental data and a model of the system to make the system as efficient as possible.

• Currently, the strain gages mounted on the Wrist Rocket are not used. Referring to Figure C.1, we can observe that two different mechanical parts support each nozzle: a metal deflection plate where the strain gages are installed and the air tubing itself. Because of this parallel support, any disturbance from the tubing going to the nozzles would affect the force readings from the gages. When the device is wrapped around the arm, a simple twist of the forearm is enough to offset the gages. This could be avoided by installing the gages on the tubes themselves, using rectangular profile tubing. This obviously requires a major change in the design of the Wrist Rocket. Attempts were made to study the concept but were never completed.

• Design a better fixing technique to attach the device to the arm. The current situation allows significant motion with the arm. One solution tested was to insert an inflatable balloon between the cuff and the wrist. This appeared to be mechanically good but not very practical because the balloon would compress the radial artery that passes through the region.

• Air pressure up to 115 psi can produce significant force perturbations, enough to displace a human arm a significant magnitude over the resolution of the TRACK/SELSPO. However, noise will always be an issue and it is not likely that it can be easily solved.
APPENDIX D

MISCELLANEOUS DEVELOPMENTS

D.1 ANALYSIS OF GYROSCOPIC EFFECTS DURING DRILL OPERATION

Due to the high rotating speed of some mechanical parts of the drill, gyroscopic induced torques may be felt by the operator when he/she rotates the drill about the tip. Because the gyroscopic effects are at right angle with the drill motion, this non intuitive behavior of the drill can eventually affect the subject control strategy if it is significant. In addition, it is important to demonstrate whether the gyroscope effect helps stabilize the drill for a given orientation.

During normal drilling operation, the drill is assumed to be oriented perpendicular to the working piece. Because of positioning accuracy of the human hand, the drill might slowly drift away from the axis of rotation of the drill, namely the axis along O-D in Figure D.1. This dynamic situation is equivalent to a gyroscope that can undergo a procession motion if disturbed from its original orientation. On the basis of the drill specification sheets and experimental data, the angular velocity \( \omega \), also called spinning velocity, is around 20 Hz or 125 rad/s. The total mass of the drill is 1.48 kg and to be very conservative in our estimate, let's assume that this is the total mass of the spinning mechanical parts and that it is uniformly distributed. Assume also that the drill is initially oriented along \( OX \). Let's now consider what happens at the onset of drill motion. We can consider that the downward motion of the drill is a forced procession velocity \( \Omega \) which can be estimated to 1 rad/s to be very conservative. This motion induces a differential momentum change in the \( Y \) positive direction, which produces a torque \( M \) on the human hand in the \( Y \) negative direction. This moment tends to bring the hand away from its original position, thus, it does not help to bring it back along the axis \( OX \) immediately. Figure D.2 illustrates the initial induced torque on the hand for different initial movements of the point \( D' \) of the drill.
FIGURE D.1 Gyroscopic model of the drill.
The torque $M$ that is produced is approximately given by:

$$M = I\Omega \times \ddot{\omega},$$  \hspace{1cm} (D.1)

and its magnitude by $|M| = I\Omega \omega$, where $I$ is the moment of inertia of the spinning mechanical parts about the axis $O-J$. Notice that for this development, the whole drill mass is assumed to be spinning and precessing. We can estimate $I$ by assuming that the drill mass is contained into a cylinder of diameter equal to 4 cm:

$$I = \frac{1}{2}MR^2 \cong 3 \times 10^{-4} \text{ Kg} \cdot \text{m}^2$$  \hspace{1cm} (D.2)

Therefore, the induced torque is,

$$M = 3 \times 10^{-4} \times 1 \times 125 = 0.0375 \text{Nm}$$  \hspace{1cm} (D.3)

In comparison, the torque about point $O$ due to gravity is about 1.5 Nm. Therefore, the gyroscopic effect, due to motion of the hand, seems to be negligible.
FIGURE D.2 Direction of induced torque on the hand by a given drill motion.
D.2 FINDING ORIENTATION OF THE CART IN THE LABORATORY REFERENCE FRAME

Because of the limited range of view of the SELSPOT cameras, the cart used to perform the drill experiments was oriented at a certain angle to the vertical plane that faces the cameras. This rotation is mainly about the $Y$ axis of the laboratory reference frame. The angle varied from one experiment to another. Therefore, two simple techniques were designed to estimate its value. The angle was used to rotate the kinematic data into the laboratory reference frame for further analysis.

With the first technique, a special marker with LEDs (a plate 7"x8") was fixed perpendicular to the vertical sliding panel of the cart. Knowledge of the fourth quaternion component of the marker gives the required angle $\theta$ easily. Based on the review of quaternions in Appendix A,

$$\theta = 2 \tan^{-1}(q_4)$$  \hspace{1cm} (D.4)

In a second technique, which was finally selected for the experiments, the angle was estimated by fitting a plane to the location of the drill tip for all the experiments performed in the LOCATION tests. The angle of rotation of the plane about the $Y$ axis is then computed. A normal pseudo inverse techniques is used to find the coefficients of the equation of the plane. Given the general equation of a plane:

$$Ax + By + Cz + D = 0,$$  \hspace{1cm} (D.5)

a matrix $M$ is formed with rows of $M$ containing the $X,Y,Z$ coordinates of each point. Selecting $D = 1$ in equation D.5, the values of $A$, $B$ and $C$ are obtained as follows:

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = (M'M)^{-1}M' \begin{bmatrix} -1 \\ \vdots \\ -1 \end{bmatrix}$$  \hspace{1cm} (D.6)

The angle $\theta$ is then given by

$$\theta = \tan^{-1}\left(\frac{-C}{A}\right).$$  \hspace{1cm} (D.7)

This pseudo-inverse techniques had a precision of 1 degree for all subjects.
APPENDIX E

INFORMED CONSENT DOCUMENT

Title of study: Measurement of 3D impedance of the human arm.
Principal Investigator: Prof. Neville Hogan
Associated Investigator: Denis Rancourt

PURPOSE OF STUDY

At the moment, there exists no data describing the human arm dynamic behavior in space. Knowledge of the dynamic characteristics would benefit, in particular, the study of human arm control and the improvement of tool ergonomics. There is some evidence that humans take advantage of the inherent mechanical properties of the arm to perform various motions with their arm. However, very little is known about whether the arm dynamic behavior has a major role in the control of powered tools. Besides, such tools produce vibrations which are thought to be harmful to the human body. We believe that the dynamic behavior of the arm could be an important factor in the control of the risks to suffer from physiological pathologies due to the vibrations. The dynamic response of a limb to perturbation can be described by its mechanical impedance. Hence, the purpose of the study is to characterize the 3D impedance of the arm while the subject is performing particular interacting tasks. Analysis of the data is intended to provide information on the control of tools by humans and the effect of impedance on the transmission of vibrations to the arm. A force perturbation device, the Wrist Rocket, is used to measure the arm impedance.

EXPERIMENTAL PROTOCOL

The subject will perform two types of experiment. In the first experiment, the subject will operate common powered tools (e.g. drill, sander) at different orientations in space. During the task, the arm posture and electromyography activity of the principal muscle groups of the arm will be recorded. The arm posture will be tracked by the SELSPOT/TRACK System (see description below): light-emitting diodes, mounted at different locations on the arm, will be monitored by two electronic cameras. The purpose of this experiment is to identify the arm posture that subjects use while performing the task. We are also interested to describe how the posture and muscle activation vary with the "mean" force magnitude applied on the tool.
The purpose of the second experiment is to measure the 3D impedance of the arm for the postures described in the first experiment. While the subject will be holding the appropriate posture, he will push or pull on a spring in order to simulate unstable and stable loads at the hand (see Figure 1). Various load levels will be tested to investigate the modulation of arm posture and EMG with "mean" force magnitude. While the subject is performing the task, the posture and EMG activity will be recorded, as in the first experiment. Force perturbations pulses (of magnitude less than a pound) will be applied at the wrist in order to measure the arm impedance. The force will be provided by the Wrist Rocket (described below), an air jet system fixed on a plastic cuff that will be wrapped around the wrist.

The two experiments will be performed during two different sessions.

**RISKS AND BENEFITS**

There are several safety issues related to these experiments. The SELSPOT/TRACK system and EMG recording equipment pose no known risk to the subject and have been used safely for decades now. The powered tools utilized for the study are commercially available and the risks associated with them would occur only if the subject loses control of the tools. Therefore, we will make sure that for the arm postures selected, the subject can keep proper control and stability over the tools. Safety of the Wrist Rocket and the required precautions are described below.

**Description of the Wrist Rocket**

The Wrist Rocket is a pneumatic system, designed in the Newman Laboratory, that can produce thrusts of up to about a pound or less in any of three orthogonal directions in space. The force level is just enough to perturb the arm without giving discomfort to the subject. The system is illustrated in Figure 2. The Wrist Rocket functions in the following way. Air, coming from the air receiver, flows to the Wrist Rocket cuff. It enters the chamber of a pneumatic valve located on the cuff which is clamped around the wrist of the subject (Figure 2). Each axis (X,Y,Z) has a valve that directs the air flow either in the positive or negative direction. The valve is controlled by a hydraulic line connected to each chamber. The line provides a 1000 psi oil pressure from servo-valves fixed on a cart. In typical operation, the valve piston slides back and forth to produce thrust pulses at the wrist. If anything goes wrong, the subject and the experimenter hold a button in their hand that, when released, shuts off the air and oil supplies within 200 msec.

**PNEUMATIC:**

The air source is a compressor and receiver, the output of which is regulated to around 160 Psi. A safety valve (set at 225 psi) is also installed on the receiver. Although 160 psi is a much lower pressure than that encountered in bottled gas applications, the following safety precautions have been taken:
• **embolism**: nozzles on the wrist cuff are specially designed such that there is a path for air to escape radially, if the nozzle comes in contact with the skin (see Figure 3). This prevents embolism due to air penetrating the skin.

• **hose whipping**: all tubing and fittings are standard pneumatic hardware securely tightened to the Wrist Rocket and the supply line (pressure rating of tubing's: 2500 psi; fittings are designed to operate to up to 300 psi).

• **high velocity jet**: to protect the eyes of the subject from high air velocity which could contain particles, the subject will wear safety goggles. A filter is installed upstream of the Wrist Rocket to retain most of the particles.

• **noise**: the air coming out of the nozzles produces noise level of up to 115 db, in the medium-high range of frequencies. To decrease the noise to a safe level (for the experimental time period), the subject and experimenter both wear ear plugs and/or ear muffs.

**HYDRAULIC:**

The hydraulic source is a 1000 psi compressor with safety valves. The hydraulic hardware has been used for several years without any problem. The hydraulic line going from the cart to the cuff is attached to the cuff with an appropriate "hydraulic application" glue. The hydraulic fluid is so viscous that in case of a leak, the output velocity of the fluid is small enough not to hurt the subject. However, no such accidents have happened during the several years of use of other hydraulically powered devices in the Newman laboratory.

**ELECTRIC:**

Some electrical circuitry is located on the Wrist Rocket, to power the strain gage systems. It draws very little power (15 V, 15 watts) and is well isolated from the subject. Therefore, it represents no potential danger.

**Description of SELSPOT/TRACK**

TRACK is an optoelectronic photogrammetric device that measures spatial kinematics of LED (Light-emitting diodes) markers in the 3D space. TRACK was designed at the Newman Laboratory at MIT. The system is based on two infrared SELSPOT cameras that use lateral-photo-effect diodes to provide X and Y locations of the markers in space. Markers are LED assembled in bundles of three in order to increase the luminosity. A set of four LED bundles are placed onto a cross shape Plexiglas plate to compose an array. One array is fixed at each location of the arm where we need to measure the kinematics. The arrays are attached with Velcro and elastic bands that are wrapped around the arm. The tension of the bands is kept at a level that does not restrict the blood circulation.

There are no benefits to the experimental subject beyond the satisfaction of contributing to advances in the understanding of the physiology pertinent to prosthetics, human movement and biomechanics. Throughout the experiments, we welcome and encourage any questions, comments, or suggestions that you might have regarding the experiments.
SUBJECTS COMMENTS CONCERNING THE EXPERIMENT

The subject agrees to the following:

I am free at any time to seek further information regarding the experiment. In addition, I am also free to withdraw consent and discontinue participation at any time.

The subject will remain anonymous in all publications of the results of this experiment.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the M.I.T. Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights. Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T. 253-1772, if I feel I have been treated unfairly as a subject.

I have read the above consent document and understand the experiments described in the document. I agree to participate in the experiments as a subject.

The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

Date: ______________________

Subject's Name: ______________________

Subject's Signature: ______________________

Witness Name: ______________________

Witness signature: ______________________
SUBJECT INTERVIEW

Title of study: Measurement of 3D impedance of the human arm.
Principal Investigator: Prof. Neville Hogan
Associated Investigator: Denis Rancourt

QUESTIONS

Subject's Name:

Subject's Age:

Subject's Sex: Male Female

Subject's Handedness: Right Left

Subject's Height:

Subject's Weight.

Subject's shoulder height:

arm length:

forearm length:

hand length:

Does the subject have any neuromuscular condition affecting the function of the right or left shoulder, arm or hand?
APPENDIX F

FIGURES FOR ALL SUBJECTS

Appendix F contains all Figures of the experimental data for the postural experiment (Figures F.1 to F.237) and the stiffness experiment (Figures F.238 to F.261). The Figures are compiled as follows.

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**TABLE F.1** List of Figures for postural experiment data
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**TABLE F.2** List of Figures for stiffness experiment data

In order to better understand the content of each Figure, it is advisable to consult the main text in the thesis. However, a few comments are added in this section.

**F.1 STICK PLOTS**

Stick plots are used to graphically represent the upper limb posture of subjects, along with the drill, for the postural experiments. For a given subject, there are two stick plot Figures for each of the four different tests performed (LOCATION, FORCE, LENGTH, DRILL OFF). The first Figure illustrates data for all trials that were realized in one particular test. The second Figure is the average of each group of data i.e. all trials for a given drilling location and a given test. Each Figure contains three graphs which represent the lateral view of the subject when drilling (bottom right graph), the frontal view i.e. from behind the vertical panel on which subjects were drilling (bottom left graph), and a top view (top right graph). On each graph, the upper limb is represented by plain stick lines which connect the markers of the C7 vertebra location, the shoulder, the elbow and the middle of the hand, and dashed lines which connect three strategic points of the drill: the handle, the 90 degree angle and the tip of the drill bit. Stick plots for drilling locations 5 and 6 are dotted line segments instead of plain line segments. When any of the markers is not valid, segments do not connect to it and it is not represented on the graph. Valid markers which are not connected to adjacent valid ones are represented by an empty circle.
F.2 GROOD & SUNTAY 3D ANGLES

In order to graphically illustrate the joint angles of each of the upper limb joints (shoulder, elbow, wrist), two Figures are used for each subject, for each of the four different tests. The first Figure illustrates the 3D Grood&Suntay angles. The Figure contains 4 graphs. The top left graph illustrates all three joint data, the top right graph, the wrist data; the bottom left graph, the elbow data and the bottom right graph, the shoulder data. Each graph is made up of a series of points which graphically represent the rotation matrix of a particular joint. Each point is the locus of a three element vector that contains the Flexion/Extension angle, the External/Internal rotation angle, and the Abduction/Adduction angle of a particular joint. These angles, called the Grood & Suntay angles are described in Chapter 3. The symbols used for the points were the following: (o) for data of drilling locations 1 and 4, (*) for data of drilling location 2 or 5, and (+) for data of drilling locations 3 or 6. Straight lines represent the main eigenvector of the cloud of points of a particular joint, for all drilling locations. The second Figure represents the same data but projected on the main eigenvector.

F.3 LINEAR ANGLES

Each of the projected angles on the main eigenvector, illustrated on the second Figure of the Grood&Suntay angle graphs, is located at a certain distance from the mean of the data of drilling location 4. This distance, computed along the main eigenvector, is plotted in the Figure of Linear angle plots. There is one plot for each subject, for each of the four different tests performed. These plots are divided by vertical dotted lines to separate the different points of a same drilling location. The Figure contains three plots, one for each of the upper limb joints.

F.4 UPPER LIMB DESCRIPTOR PLOTS

In Chapter 5, we have defined a series of upper limb descriptors: the VTS, VTE, VTSVDR, VTEVDR, VDRh, VDRv and EF angles. The angles are plotted on any of the two Figures for each subject, for each of the four different tests performed. These plots are divided by vertical dotted lines to separate the different points of a same drilling location.
F.5 STATISTICAL ANALYSIS RESULTS

Upper limb posture of a subject was statistically compared by analyzing the linear angles that were discussed in section F.2. Comparison of posture between different drilling locations (e.g. posture at location 2 versus posture at location 5) are done using three different statistical t tests (Duncan, 1974) one at 2% significance, one at 5% significance, and one at 10% significance. The symbols $n_1$ and $n_2$ respectively represent the number of data points in group 1 and group 2; $s_{equal}$ represents the equivalent standard deviation, $m_0$ represents the number of DOF, and $e$ is an intermediate parameter to compute $m_0$.

F.6 THE PLOTS OF POSTURAL AND STIFFNESS EXPERIMENTS FOR ALL SUBJECTS

The plots are described in Chapter 6. As a reminder, the top right plots contain both force and displacement data. For practical purposes, the scales were set for the displacement data. For the force data, the scales should be in Newtons and not millimeters.
FIGURE F.1 Stick plots of upper limb; LOCATION test, subject 1.
FIGURE F.2 Averaged stick plots of upper limb; LOCATION test, subject 1.
FIGURE F.3 Stick plots of upper limb, LOCATION test, subject 2.
FIGURE F.4 Averaged stick plots of upper limb; LOCATION test, subject 2.

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FIGURE F.5 Stick plots of upper limb; LOCATION test, subject 3.
FIGURE F.6 Averaged stick plots of upper limb; LOCATION test, subject 3.
FIGURE F.7 Stick plots of upper limb; LOCATION test, subject 4.
FIGURE F.8 Averaged stick plots of upper limb, LOCATION test, subject 4.
FIGURE F.9 Stick plots of upper limb; LOCATION test, subject 5
FIGURE F.10 Averaged stick plots of upper limb; LOCATION test, subject 5.
FIGURE F.11 Stick plots of upper limb, LOCATION test, subject 6.
FIGURE F.12  Averaged stick plots of upper limb; LOCATION test, subject 6.
FIGURE F.13 Stick plots of upper limb, LOCATION test, subject 7.
FIGURE F.14 Averaged stick plots of upper limb; LOCATION test, subject 7.
FIGURE F.15 Stick plots of upper limb; LOCATION test, subject 8.
FIGURE F.16 Averaged stick plots of upper limb, LOCATION test, subject 8.
FIGURE F.17 Grood&Suntay 3D angle; LOCATION test, subject 1.
FIGURE F.18 Projected Grood & Suntay 3D angle; LOCATION test, subject 1.
FIGURE F.19 Grood & Suntay 3D angle; LOCATION test, subject 2.

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FIGURE F.20  Projected Grood&Suntay 3D angle, LOCATION test, subject 2.
FIGURE F.21 Grood & Suntay 3D angle, LOCATION test, subject 3.

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FIGURE F.22  Projected Grood&Suntay 3D angle; LOCATION test, subject 3.
FIGURE F.23 Grood&Suntay 3D angle; LOCATION test, subject 4.
FIGURE F.24 Projected Grood & Suntay 3D angle; LOCATION test, subject 4.
FIGURE F.25 Grood&Suntay 3D angle; LOCATION test, subject 5.
FIGURE F.26 Projected Grood&Suntay 3D angle; LOCATION test, subject 5.
FIGURE F.27 Grood & Suntay 3D angle; LOCATION test, subject 6.

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FIGURE F.28 Projected Grood & Suntay 3D angle; LOCATION test, subject 6.
FIGURE F.29 Grood & Suntay 3D angle; LOCATION test, subject 7.
FIGURE F.30 Projected Grood&Suntay 3D angle; LOCATION test, subject 7.
FIGURE F.32 Projected Grood & Sunta 3D angle; LOCATION test, subject 8.
FIGURE F.33 Linear angles, LOCATION test, subject 1.
FIGURE F.34 Linear angles; LOCATION test, subject 2.
FIGURE F.35 Linear angles; LOCATION test, subject 3.
FIGURE F.37 Linear angles; LOCATION test, subject 5.
FIGURE F.38 Linear angles; LOCATION test, subject 6.
FIGURE F.40 Linear angles; LOCATION test, subject 8.
FIGURE F.41 VTS, VTE, VTSVDR and VTEVDR angles; LOCATION test, subject 1.
FIGURE F.42  VDRh, VDRv and EF angles; LOCATION test, subject 1.
FIGURE F.43 VTS, VTE, VTSVDR and VTEVDR angles; LOCATION test, subject 2.
FIGURE F.44 VDRh, VDRv and EF angles, LOCATION test, subject 2.
FIGURE F.45 VTS, VTE, VTSVDR and VTEVDR angles; LOCATION test, subject 3.
FIGURE F.46  VDRh, VDRv and EF angles; LOCATION test, subject 3.
FIGURE F.47 VTS, VTE, VTSVDR and VTEVDR angles; LOCATION test, subject 4.
FIGURE F.48 VDRh, VDRv and EF angles; LOCATION test, subject 4.
FIGURE F.49  VTS, VTE, VTSVDR and VTEVDR angles; LOCATION test, subject 5.
FIGURE F.50  VDRh, VDRv and EF angles; LOCATION test, subject 5.
FIGURE F.51 VTS, VTE, VTSVDR and VTEVDR angles; LOCATION test, subject 6.
FIGURE F.52 VDRh, VDRv and EF angles; LOCATION test, subject 6.
FIGURE F.53  VTS, VTE, VTSVDR and VTEVDR angles; LOCATION test, subject 7.
FIGURE F.54 VDRh, VDRv and EF angles, LOCATION test, subject 7.
FIGURE F.55 VTS, VTE, VTSVDR and VTEVDR angles, LOCATION test, subject 8.
FIGURE F.56 VDRh, VDRv and EF angles; LOCATION test, subject 8.

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**COMPARISON POINT 2 VS POINT 5**

- **wrist angle, 2 vs 5**
  - \( 5,000 \) vs \( 5,000 \)
  - 3.2126, 0.8358, 2.0964, 2.1601, 2.8590, 7.8516, 0.5643

- **elbow angle, 2 vs 5**
  - \( 5,000 \) vs \( 5,000 \)
  - 3.0593, 9.3249, 3.1430, 2.4470, 1.9430, 5.5214, 0.1650

- **shoulder angle, 2 vs 5**
  - \( 5,000 \) vs \( 5,000 \)
  - 3.0284, 4.4886, 2.3860, 2.3460, 1.8640, 7.9982, 0.4925

**COMPARISON POINT 3 VS POINT 6**

- **wrist angle, 3 vs 6**
  - \( 5,000 \) vs \( 5,000 \)
  - 2.6557, 1.6231, 3.1430, 2.4470, 1.3430, 5.9035, 0.7982

- **elbow angle, 3 vs 6**
  - \( 5,000 \) vs \( 5,000 \)
  - 3.0284, 4.4886, 2.3860, 2.3460, 1.8640, 7.9982, 0.4925

- **shoulder angle, 3 vs 6**
  - \( 5,000 \) vs \( 5,000 \)
  - 2.2860, 1.3018, 3.1430, 2.4470, 1.9430, 6.2016, 0.7691

**COMPARISON POINT 2 VS POINT 3**

- **wrist angle, 2 vs 3**
  - \( 5,000 \) vs \( 5,000 \)
  - 2.8699, 9.2454, 2.9980, 2.3650, 1.9050, 7.0111, 0.3123

- **elbow angle, 2 vs 3**
  - \( 5,000 \) vs \( 5,000 \)
  - 2.6495, 2.3146, 2.9980, 2.3650, 1.9050, 7.1315, 0.6745

- **shoulder angle, 2 vs 3**
  - \( 5,000 \) vs \( 5,000 \)
  - 5.4188, 2.4267, 3.1430, 2.4470, 1.9430, 6.1650, 0.7720

**COMPARISON H-S DISTANCE POINT 2 VS POINT 5**

- **H-S distance, 2 vs 5**
  - \( 5,000 \) vs \( 5,000 \)
  - 0.0205, 0.4678, 2.8060, 2.7060, 1.8640, 7.9044, 0.5550

- **H-S distance, 3 vs 6**
  - \( 5,000 \) vs \( 5,000 \)
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### FIGURE 5.9: Statistics on linear angles, LOCATION test, subject 5 and subject 6.

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\textbf{Sample Size} & \textbf{Sample Mean} & \textbf{Sample Standard Deviation} & \textbf{Sample Median} & \textbf{Sample Mode} & \textbf{Sample Skewness} & \textbf{Sample Kurtosis} & \textbf{Sample Range} & \textbf{Sample Variance} \\
\hline
\textbf{COMPARISON POINT 2 VS POINT 5} & & & & & & & & \\
\textbf{wrist angle, 2 vs 5} & & & & & & & & \\
\textbf{elbow angle, 2 vs 5} & & & & & & & & \\
\textbf{shoulder angle, 2 vs 5} & & & & & & & & \\
\hline
\textbf{COMPARISON POINT 3 VS POINT 6} & & & & & & & & \\
\textbf{wrist angle, 3 vs 6} & & & & & & & & \\
\textbf{elbow angle, 3 vs 6} & & & & & & & & \\
\textbf{shoulder angle, 3 vs 6} & & & & & & & & \\
\hline
\textbf{COMPARISON POINT 2 VS POINT 3} & & & & & & & & \\
\textbf{wrist angle, 2 vs 3} & & & & & & & & \\
\textbf{elbow angle, 2 vs 3} & & & & & & & & \\
\textbf{shoulder angle, 2 vs 3} & & & & & & & & \\
\hline
\textbf{COMPARISON H-S DISTANCE POINT 2 VS POINT 3, POINT 3 VS 6} & & & & & & & & \\
\textbf{H-S distance, 2 vs 5} & & & & & & & & \\
\textbf{H-S distance, 3 vs 6} & & & & & & & & \\
\end{tabular}
FIGURE F.61 Stick plots of upper limb, FORCE test, subject 1.
FIGURE F.62 Averaged stick plots of upper limb; FORCE test, subject 1.
FIGURE F.63 Stick plots of upper limb; FORCE test, subject 2.
FIGURE F.64  Averaged stick plots of upper limb; FORCE test, subject 2.

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**FIGURE F.66** Averaged stick plots of upper limb; FORCE test, subject 3.
FIGURE F.67 Stick plots of upper limb; FORCE test, subject 4.
FIGURE F.68 Averaged stick plots of upper limb; FORCE test, subject 4.
FIGURE F.69 Stick plots of upper limb, FORCE test, subject 5.
FIGURE F.70 Averaged stick plots of upper limb; FORCE test, subject 5.
FIGURE F.71 Stick plots of upper limb, FORCE test, subject 6.
FIGURE F.72  Averaged stick plots of upper limb; FORCE test, subject 6.
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FIGURE F.74 Averaged stick plots of upper limb; FORCE test, subject 7.
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FIGURE F.80 Projected Grood&Suntay 3D angle; FORCE test, subject 2.
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FIGURE F.84 Projected Grood&Suntay 3D angle; FORCE test, subject 4.

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FIGURE F.86 Projected Grood & Suntay 3D angle; FORCE test, subject 5.
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FIGURE F.89 Grood&Suntay 3D angle; FORCE test, subject 7.

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FIGURE F.91 Grood&Suntay 3D angle; FORCE test, subject 8.
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FIGURE F.94 Linear angles; FORCE test, subject 2.
FIGURE F.95 Linear angles; FORCE test, subject 3.
FIGURE F.96 Linear angles; FORCE test, subject 4.

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FIGURE F.99 Linear angles; FORCE test, subject 7.
FIGURE F.100 Linear angles; FORCE test, subject 8.
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FIGURE F.102 VDRh, VDRv and EF angles; FORCE test, subject 1.
FIGURE F.103 VTS, VTE, VTSVDR and VTEVDR angles; FORCE test, subject 2.
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FIGURE F.111 VTS, VTE, VTSVDR and VTEVDR angles, FORCE test, subject 6
FIGURE F.112 VDRh, VDRv and EF angles; FORCE test, subject 6.
FIGURE F.113 VTS, VTE, VTSVDR and VTEVDR angles; FORCE test, subject 7.
FIGURE F.114 VDRh, VDRv and EF angles; FORCE test, subject 7.
FIGURE F.115 VTS, VTE, VTSVDR and VTEVDR angles; FORCE test, subject 8.
FIGURE F.116 VDRh, VDRv and EF angles; FORCE test, subject 8.
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**COMPARISON OF FORCE LEVELS, PT 2**

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**COMPARISON OF H-S DISTANCE, POINT 2 VS POINT 3**

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**COMPARISON OF FORCE LEVELS, POINT 2**

**Wrist pt 2**, low vs high force level
- 5.0000  5.0000  5.0071  1.006  2.9980  2.1650  1.8950  0.0120  0.0612

**Elbow pt 2**, low vs high force level
- 5.0000  5.0000  10.0014  1.148  2.8960  2.3060  1.8600  7.7496  0.5899

**Shoulder pt 2**, low vs high force level
- 5.0000  5.0000  7.4175  1.2404  2.9980  2.3650  1.8950  6.5559  0.7347

**Wrist pt 2**, low vs medium force level
- 5.0000  5.0000  3.7290  1.0116  2.8960  2.3060  1.8600  7.8680  0.5648

**Elbow pt 2**, low vs medium force level
- 5.0000  5.0000  9.0191  1.1513  2.9980  2.3650  1.8950  6.6493  0.7253

**Shoulder pt 2**, low vs medium force level
- 5.0000  5.0000  7.2879  0.8803  3.1430  2.4470  1.9430  6.2868  0.7610

**Wrist pt 2**, high vs medium force level
- 5.0000  5.0000  4.8239  0.3246  2.9980  2.3650  1.8950  6.5029  0.7399

**Elbow pt 2**, high vs medium force level
- 5.0000  5.0000  7.9602  0.1339  2.9980  2.3650  1.8950  7.3602  0.6474

**Shoulder pt 2**, high vs medium force level
- 5.0000  5.0000  5.2242  0.8122  2.8960  2.3060  1.8600  7.9612  0.5349

**COMPARISON OF FORCE LEVELS, POINT 3**

**Wrist pt 3**, low vs high force level
- 5.0000  5.0000  2.3065  1.0642  2.9980  2.3650  1.8950  7.1028  0.3223

**Elbow pt 3**, low vs high force level
- 5.0000  5.0000  7.8196  1.6772  2.9980  2.3650  1.8950  7.4692  0.3667

**Shoulder pt 3**, low vs high force level
- 5.0000  5.0000  5.0534  1.0306  3.1430  2.4470  1.9430  5.8262  0.1946

**Wrist pt 3**, low vs medium force level
- 5.0000  5.0000  1.5752  2.8949  2.9980  2.3650  1.8950  7.0139  0.6875

**Elbow pt 3**, low vs medium force level
- 5.0000  5.0000  5.5609  0.2643  2.9980  2.3650  1.8950  6.6725  0.7230

**Shoulder pt 3**, low vs medium force level
- 5.0000  5.0000  2.3650  0.5046  2.9980  2.3650  1.8950  7.3792  0.3550

**Elbow pt 3**, high vs medium force level
- 5.0000  5.0000  1.9806  1.2422  2.9980  2.3650  1.8950  6.7371  0.2811

**Shoulder pt 3**, high vs medium force level
- 5.0000  5.0000  2.3650  0.5046  2.9980  2.3650  1.8950  7.3792  0.3550

**Wrist pt 3**, high vs medium force level
- 5.0000  5.0000  4.6166  2.3510  2.4670  2.0480  1.7010  27.7558  0.3460

**Elbow pt 3**, high vs medium force level
- 5.0000  5.0000  1.3116  0.7717  2.4670  2.0480  1.7010  27.9133  0.4721

**Shoulder pt 3**, high vs medium force level
- 5.0000  5.0000  2.3650  0.5046  2.9980  2.3650  1.8950  7.3792  0.3550

**COMPARISON OF H-S DISTANCE, POINT 2**

**H-S distance, pt 2**, low vs high
- 5.0000  4.0000  0.0182  2.4128  3.7470  2.7760  2.1320  4.3210  0.9611

**H-S distance, pt 2**, low vs medium
- 5.0000  5.0000  0.0209  0.2190  2.9980  2.3650  1.8950  6.5820  0.7321

**H-S distance, pt 2**, high vs medium
- 4.0000  5.0000  0.0114  2.4619  3.3650  2.5710  2.0150  4.8548  0.9996

**COMPARISON OF H-S DISTANCE, POINT 3**

**H-S distance, pt 3**, low vs high
- 5.0000  5.0000  0.0202  0.3040  3.3650  2.5710  2.0150  5.4842  0.8386

**H-S distance, pt 3**, low vs medium
- 5.0000  5.0000  0.0207  0.4946  3.1430  2.4470  1.9430  5.8977  0.7985

**H-S distance, pt 3**, high vs medium
- 5.0000  5.0000  0.0123  0.5810  2.8960  2.3060  1.8600  7.8574  0.4326

**COMPARISON OF H-S DISTANCE, POINT 2 VS POINT 3**

**H-S distance, pt 2 vs pt 3**
- 14.0000  15.0000  0.0114  0.3272  2.4850  2.0600  1.7080  24.6873  0.6344
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**COMPARISON OF FORCE LEVELS, POINT 2 VS POINT 3**

- **Wrist pt 2 vs pt 3**
  - 15.0000 | 15.0000 | 1.0921 | 13.8918 | 2.4730 | 2.0520 | 1.7030 | 26.6882 | 0.6199
- **Elbow pt 2 vs pt 3**
  - 15.0000 | 15.0000 | 3.1157 | 7.7971 | 2.5180 | 2.0800 | 1.7210 | 21.1698 | 0.7840
- **Shoulder pt 2 vs pt 3**
  - 15.0000 | 15.0000 | 1.2292 | 17.4584 | 2.4790 | 2.0560 | 1.7060 | 25.6975 | 0.3503

**COMPARISON OF H-S DISTANCE, POINT 2**

- **H-S distance, pt 2, low vs high**
  - 5.0000 | 4.0000 | 0.0100 | 3.8625 | 3.3650 | 2.5710 | 2.0150 | 5.2006 | 0.8225
- **H-S distance, pt 2, low vs medium**
  - 5.0000 | 5.0000 | 0.0131 | 0.4057 | 2.8960 | 2.3650 | 1.8600 | 7.9996 | 0.5037
- **H-S distance, pt 2, high vs medium**
  - 4.0000 | 5.0000 | 0.0100 | 4.4214 | 3.3650 | 2.5710 | 2.0150 | 5.2168 | 0.1392

**COMPARISON OF H-S DISTANCE, POINT 3**

- **H-S distance, pt 3, low vs high**
  - 5.0000 | 5.0000 | 0.0084 | 3.5355 | 2.8960 | 2.3650 | 1.8600 | 9.7985 | 0.5228
- **H-S distance, pt 3, low vs medium**
  - 5.0000 | 5.0000 | 0.0100 | 0.3440 | 2.9980 | 2.3650 | 1.8950 | 7.4717 | 0.3670
- **H-S distance, pt 3, high vs medium**
  - 5.0000 | 5.0000 | 0.0099 | 4.9106 | 2.9980 | 2.3650 | 1.8950 | 7.3081 | 0.3461

**COMPARISON OF H-S DISTANCE, POINT 2 VS POINT 3**

- **H-S distance, pt 2 vs pt 3**
  - 14.0000 | 15.0000 | 0.0097 | 0.7089 | 2.4730 | 2.0520 | 1.7030 | 26.9749 | 0.4967
### COMPARISON OF FORCE LEVELS, PT 2

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**COMPARISON OF FORCE LEVELS, POINT 3**

| wrist pt 3, low vs high force level | 5.0000 | 5.0000 | 0.8999  | 1.4698 | 2.8960 | 2.3060   | 1.8600 | 7.7619 | 0.4124 |
| elbow pt 3, low vs high force level | 5.0000 | 5.0000 | 2.2356  | 0.2422 | 2.8960 | 2.3060   | 1.8600 | 7.9849 | 0.4783 |
| shoulder pt 3, low vs high force level | 5.0000 | 5.0000 | 1.8359  | 0.1203 | 3.1430 | 2.4470   | 1.9430 | 5.7303 | 0.8147 |
| wrist pt 3, low vs medium force level | 5.0000 | 5.0000 | 1.2265  | 0.4309 | 3.1430 | 2.4470   | 1.9430 | 6.1111 | 0.2220 |
| elbow pt 3, low vs medium force level | 5.0000 | 5.0000 | 2.3330  | 1.0883 | 2.8960 | 2.3060   | 1.8600 | 7.9119 | 0.2120 |
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### COMPARISON OF FORCE LEVELS, POINT 2 VS POINT 3

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### COMPARISON OF H-S DISTANCE, POINT 2

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### COMPARISON OF H-S DISTANCE, POINT 2 VS POINT 3

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## COMPARISON OF FORCE LEVELS, PT 2

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## COMPARISON OF H-S DISTANCE, POINT 2

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## COMPARISON OF H-S DISTANCE, POINT 3

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FIGURE F.125 Stick plots of upper limb; LENGTH test, subject 2
FIGURE F.126  Averaged stick plots of upper limb; LENGTH test, subject 2
FIGURE F.127  Stick plots of upper limb; LENGTH test, subject 3
FIGURE F.128 Averaged stick plots of upper limb, LENGTH test, subject 3

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FIGURE F.129 Stick plots of upper limb; LENGTH test, subject 4
FIGURE F.130  Averaged stick plots of upper limb; LENGTH test, subject 4
FIGURE F.131 Stick plots of upper limb; LENGTH test, subject 5
FIGURE F.132  Averaged stick plots of upper limb, LENGTH test, subject 5
FIGURE F.133 Stick plots of upper limb; LENGTH test, subject 6
FIGURE F.134  Averaged stick plots of upper limb, LENGTH test, subject 6
FIGURE F.135 Stick plots of upper limb; LENGTH test, subject 7
FIGURE F.136 Averaged stick plots of upper limb; LENGTH test, subject 7
FIGURE F.137 Stick plots of upper limb; LENGTH test, subject 8
FIGURE F.138  Averaged stick plots of upper limb, LENGTH test, subject 8
FIGURE F.139 Grood & Suntay 3D angle, LENGTH test, subject 2
FIGURE F.140  Projected Grood\&Suntay 3D angle; LENGTH test, subject 2
FIGURE F.141 Grood & Suntay 3D angle, LENGTH test, subject 3
This procedure could not be performed with this subject.
FIGURE F.143 Grood&Suntay 3D angle, LENGTH test, subject 4
FIGURE F.144  Projected Grood&Suntay 3D angle; LENGTH test, subject 4
FIGURE F.145 Grood&Suntay 3D angle, LENGTH test, subject 5
FIGURE F.146 Projected Grood & Suntay 3D angle, LENGTH test, subject 5
FIGURE F.147 Grood & Suntay 3D angle, LENGTH test, subject 6
FIGURE F.148  Projected Grood&Suntay 3D angle; LENGTH test, subject 6
FIGURE F.149 Grood&Suntay 3D angle, LENGTH test, subject 7
FIGURE F.150  Projected Grood&Sunray 3D angle; LENGTH test, subject 7
FIGURE F.151 Grood&Suntay 3D angle, LENGTH test, subject 8
FIGURE F.152 Projected Grood & Suntay 3D angle, LENGTH test, subject 8
FIGURE F.153  Linear angles, LENGTH test, subject 2
FIGURE F.154 Linear angles; LENGTH test, subject 3
FIGURE F.155 Linear angles; LENGTH test, subject 4

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FIGURE F.156 Linear angles, LENGTH test, subject 5
FIGURE F.157 Linear angles; LENGTH test, subject 6
FIGURE F.158 Linear angles; LENGTH test, subject 7
FIGURE F.159  Linear angles; LENGTH test, subject 8
FIGURE F.160 VTS, VTE, VTSVDR and VTEVDR angles, LENGTH test, subject 2
FIGURE F.161 VDRh, VDRv and EF angles; LENGTH test, subject 2
FIGURE F.162 VTS, VTE, VTSVDR and VTEVDR angles, LENGTH test, subject 3
FIGURE F.163 VDRh, VDRv and EF angles; LENGTH test, subject 3
FIGURE F.164 VTS, VTE, VTSVDR and VTEVDR angles, LENGTH test, subject 4
FIGURE F.165 VDRh, VDRv and EF angles; LENGTH test, subject 4
FIGURE F.166 VTS, VTE, VTSVDR and VTEVDR angles, LENGTH test, subject 5
FIGURE F.167 VDRh, VDRv and EF angles; LENGTH test, subject 5
FIGURE F.168 VTS, VTE, VTSVDR and VTEVDR angles, LENGTH test, subject 6
FIGURE F.169  VDRh, VDRv and EF angles; LENGTH test, subject 6
FIGURE F.171 VDRh, VDRv and EF angles; LENGTH test, subject 7
FIGURE F.172  VTS, VTE, VTSVDR and VTEVDR angles, LENGTH test, subject 8
FIGURE F.173 VDRh, VDRv and EF angles; LENGTH test, subject 8
### COMPARISON OF DRILL LENGTHS, POINT 2

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### Comparison of H-S Distance: Point 2 vs Point 3

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Figure F.176: Statistics on linear angles: LENGTH test, subject 4.
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**COMPARISON OF DRILL LENGTHS, POINT 2**

| wrist pt 2, short vs long | 5.0000 | 5.0000 | 0.5481 | 0.6763 | 3.3650 | 2.5710 | 2.0150 | 5.2242 | 0.2829 |
| elbow pt 2, short vs long  | 5.0000 | 4.0000 | 0.9987 | 1.2256 | 2.9980 | 2.3650 | 1.8950 | 6.6198 | 0.4528 |
| shoulder pt 2, short vs long | 5.0000 | 5.0000 | 1.0776 | 0.8693 | 2.9980 | 2.3650 | 1.8950 | 6.7023 | 0.7200 |
| wrist pt 2, short vs medium | 5.0000 | 4.0000 | 0.6116 | 2.3022 | 3.3650 | 2.5710 | 2.0150 | 4.7170 | 0.2272 |
| elbow pt 2, short vs medium | 5.0000 | 4.0000 | 1.4500 | 1.1110 | 3.3650 | 2.5710 | 2.0150 | 4.6074 | 0.2148 |
| shoulder pt 2, short vs medium | 5.0000 | 4.0000 | 1.9748 | 0.1598 | 3.3650 | 2.5710 | 2.0150 | 4.6036 | 0.2144 |
| wrist pt 2, long vs medium | 4.0000 | 4.0000 | 0.7103 | 1.4914 | 3.1430 | 2.4470 | 1.9430 | 5.8745 | 0.4269 |
| elbow pt 2, long vs medium | 4.0000 | 4.0000 | 1.4821 | 0.2611 | 3.3650 | 2.5710 | 2.0150 | 4.7881 | 0.2484 |
| shoulder pt 2, long vs medium | 5.0000 | 4.0000 | 1.8409 | 0.3374 | 3.7470 | 2.7760 | 2.1320 | 3.6398 | 0.0959 |

**COMPARISON OF DRILL LENGTHS, POINT 3**

| wrist pt 3, short vs long | 5.0000 | 5.0000 | 0.2618 | 1.4698 | 2.8960 | 2.3060 | 1.8600 | 7.7619 | 0.4124 |
| elbow pt 3, short vs long | 5.0000 | 5.0000 | 0.5208 | 0.2422 | 2.8960 | 2.3060 | 1.8600 | 7.9849 | 0.4783 |
| shoulder pt 3, short vs long | 5.0000 | 5.0000 | 0.9722 | 1.2023 | 3.1430 | 2.4470 | 1.9430 | 5.7303 | 0.8147 |
| wrist pt 3, short vs medium | 5.0000 | 5.0000 | 0.3568 | 0.2309 | 3.1430 | 2.4470 | 1.9430 | 6.1111 | 0.2220 |
| shoulder pt 3, short vs medium | 5.0000 | 5.0000 | 0.5386 | 1.8883 | 2.8960 | 2.3060 | 1.8600 | 7.9119 | 0.4473 |

**Wrist pt 3, long vs medium**

| 5.0000 | 5.0000 | 0.9755 | 0.9167 | 3.1430 | 2.4470 | 1.9430 | 5.7878 | 0.8091 |

**Elbow pt 1, long vs medium**

| 5.0000 | 5.0000 | 0.3732 | 1.4429 | 2.9980 | 2.3650 | 1.8950 | 6.7911 | 0.2890 |

**Shoulder pt 3, long vs medium**

| 5.0000 | 5.0000 | 0.5973 | 1.3013 | 2.8960 | 2.3060 | 1.8600 | 7.9974 | 0.4909 |

**COMPARISON OF POINT 2 VS POINT 3**

| 13.0000 | 15.0000 | 0.3145 | 23.1370 | 2.5520 | 2.1010 | 1.7340 | 17.7408 | 0.1017 |

**Elbow pt 2 vs pt 3**

| 13.0000 | 15.0000 | 0.5693 | 17.2921 | 2.5670 | 2.1100 | 1.7400 | 16.8770 | 0.8281 |

**Shoulder pt 2 vs pt 3**

| 14.0000 | 15.0000 | 0.6787 | 19.4951 | 2.5180 | 2.0800 | 1.7210 | 21.2038 | 0.7426 |

**COMPARISON OF H-S DISTANCE: POINT 2**

| 5.0000 | 5.0000 | 0.0078 | 1.7942 | 2.8960 | 2.3060 | 1.8600 | 7.6208 | 0.3885 |

**H-S distance, short vs long pt 2**

| 5.0000 | 4.0000 | 0.0227 | 1.2259 | 4.5410 | 3.1820 | 2.3530 | 3.2928 | 0.0463 |

**H-S distance, short vs medium, pt 2**

| 5.0000 | 4.0000 | 0.0230 | 1.8214 | 4.5410 | 3.1820 | 2.3530 | 3.4613 | 0.0710 |

**COMPARISON OF H-S DISTANCE: POINT 3**

| 5.0000 | 5.0000 | 0.0031 | 2.4994 | 3.3650 | 2.5710 | 2.0150 | 5.0532 | 0.8818 |

**H-S distance, short vs long pt 3**

| 5.0000 | 5.0000 | 0.0073 | 2.3609 | 2.8960 | 2.3060 | 1.8600 | 7.7179 | 0.4044 |

**H-S distance, short vs medium, pt 3**

| 5.0000 | 5.0000 | 0.0060 | 5.0285 | 3.3650 | 2.5710 | 2.0150 | 4.7220 | 0.0834 |

**H-S distance, long vs medium, pt 3**

<p>| 14.0000 | 15.0000 | 0.0088 | 2.4431 | 2.5280 | 2.0860 | 1.7250 | 19.7633 | 0.7838 |</p>
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**COMPARISON OF DRILL LENGTHS, POINT 2**

- **Wrist**
  - pt 2 vs. short vs. long
    - 5,000 5,000 1.311 0.308 2.896 2.3650 1.8600 7.7578 0.583
  - pt 2, short vs. long
    - 5,000 5,000 3.128 0.077 2.8960 2.3650 1.8600 7.9278 0.547
  - pt 2, short vs. medium
    - 5,000 5,000 2.171 0.418 2.8960 2.3650 1.8600 7.9663 0.467
  - pt 2, short vs. medium
    - 5,000 5,000 2.139 0.194 2.8960 2.3650 1.8600 7.9779 0.526
  - pt 2, short vs. medium
    - 5,000 5,000 3.711 0.209 2.8960 2.3650 1.8600 7.5286 0.374
  - pt 2, short vs. medium
    - 5,000 5,000 2.815 0.227 2.9980 2.3650 1.8950 6.8282 0.278

- **Elbow**
  - pt 2, long vs. medium
    - 5,000 5,000 1.389 0.246 2.8960 2.3650 1.8600 7.8764 0.437
  - pt 2, long vs. medium
    - 5,000 5,000 3.839 0.162 2.9980 2.3650 1.8950 7.1816 0.332
  - pt 2, long vs. medium
    - 5,000 5,000 2.8697 0.359 2.9980 2.3650 1.8950 6.9429 0.304

**COMPARISON OF DRILL LENGTHS, POINT 3**

- **Wrist**
  - pt 3 vs. short vs. long
    - 5,000 5,000 3.562 1.080 3.1430 2.4470 1.9430 5.9864 0.200
  - pt 3, short vs. long
    - 5,000 5,000 7.107 0.0247 3.3650 2.5710 2.0150 4.5526 0.0649
  - pt 3, short vs. long
    - 5,000 5,000 8.932 0.6030 3.7470 2.7760 2.1320 4.0832 0.0464
  - pt 3, short vs. medium
    - 5,000 5,000 1.8644 0.1182 2.9980 2.3650 1.8950 6.5876 0.731
  - pt 3, short vs. medium
    - 5,000 5,000 2.7429 1.6546 2.8960 2.3650 1.8600 7.8718 0.456

- **Elbow**
  - pt 3, short vs. medium
    - 5,000 5,000 2.5559 0.4929 2.8060 2.3650 1.8600 7.8590 0.567
  - pt 3, long vs. medium
    - 5,000 5,000 3.3286 1.2632 3.650 2.5710 2.0150 4.7297 0.9158
  - pt 3, long vs. medium
    - 5,000 5,000 7.1779 0.6467 3.650 2.5710 2.0150 4.7120 0.9177
  - pt 3, long vs. medium
    - 5,000 5,000 8.8333 0.1109 3.7470 2.7760 2.1320 4.2970 0.9642

**COMPARISON POINT 2 VS. POINT 3**

- **Wrist**
  - pt 2 vs. pt 3
    - 15,000 15,000 1.4215 8.6272 2.5080 2.0740 1.7170 21.6508 0.2292
  - pt 2 vs. pt 3
    - 15,000 15,000 2.7452 5.6441 2.5080 2.0690 1.7140 22.8374 0.2623
  - pt 2 vs. pt 3
    - 15,000 15,000 3.8743 7.1037 2.5670 2.1100 1.7400 17.1494 0.1082

**COMPARISON OF H-S DISTANCE, POINT 2**

- H-S distance, short vs. long pt 2
  - 5,000 5,000 0.0132 0.0590 2.8960 2.3650 1.8600 8.0000 0.5006
- H-S distance, short vs. medium pt 2
  - 5,000 5,000 0.0136 0.6215 2.8960 2.3650 1.8600 7.9718 0.4713
- H-S distance, long vs. medium pt 2
  - 5,000 5,000 0.0136 0.6792 2.8960 2.3650 1.8600 7.9726 0.4707

**COMPARISON OF H-S DISTANCE, POINT 3**

- H-S distance, short vs. long pt 3
  - 5,000 5,000 0.0203 0.2040 3.3650 2.5710 2.0150 4.8018 0.0919
- H-S distance, short vs. medium, pt 3
  - 5,000 5,000 0.0998 1.6644 2.8960 2.3650 1.8600 7.6704 0.1964
- H-S distance, long vs. medium, pt 3
  - 5,000 5,000 0.0208 0.9823 3.3650 2.5710 2.0150 5.2050 0.8664

**COMPARISON OF H-S DISTANCE, POINT 2 VS. POINT 3**

- H-S distance, pt 2 vs. pt 3
  - 15,000 15,000 0.0088 2.8227 2.4790 2.0560 1.7060 25.7081 0.1307
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**COMPARISON OF DRILL LENGTHS, POINT 2**

wrist pt 2, short vs long
5.0000 5.0000 1.1767 1.6670 3.1430 2.4470 1.9430 6.3783 0.2479

elbow pt 2, short vs long
5.0000 5.0000 0.5290 1.1062 2.2960 2.1060 1.8600 7.5424 0.3768

shoulder pt 2, short vs long
5.0000 5.0000 4.3629 1.1752 2.0990 2.3650 1.8950 7.3542 0.3518

wrist pt 2, short vs medium
5.0000 5.0000 0.7786 5.147 3.1430 2.4470 1.9430 6.1181 0.7773

elevator pt 2, short vs medium
5.0000 5.0000 0.6393 6.3935 2.0906 3.1430 2.4470 1.9430 6.2184 0.2324

shoulder pt 2, short vs medium
5.0000 5.0000 5.9235 1.2210 2.0990 2.3650 1.8950 7.3526 0.3516

wrist pt 2, long vs medium
5.0000 5.0000 1.2509 1.6612 3.1430 2.4470 1.9430 6.1172 0.2274

elbow pt 2, long vs medium
5.0000 5.0000 6.3619 1.9532 2.0990 2.3650 1.8950 7.2022 0.3336

shoulder pt 2, long vs medium
5.0000 5.0000 5.9235 2.1210 2.0990 2.3650 1.8950 7.3526 0.3516

**COMPARISON OF DRILL LENGTHS, POINT 3**

wrist pt 3, short vs long
5.0000 5.0000 7.4353 1.4347 3.1430 2.5710 2.0150 5.0273 0.8845

elevator pt 3, long vs medium
5.0000 5.0000 1.1567 0.1441 2.8960 2.7060 1.8600 7.6616 0.6051

shoulder pt 3, long vs medium
5.0000 5.0000 3.3953 3.5029 2.0990 2.3650 1.8850 7.3459 0.3598

**COMPARISON OF H-S DISTANCE, POINT 2**

H-S distance, short vs long pt 2
5.0000 5.0000 0.0846 2.2712 3.7470 2.7760 1.1320 4.3000 0.9488

H-S distance, short vs medium, pt 2
5.0000 5.0000 0.0104 0.9547 2.9980 2.3650 1.8950 6.7120 0.2810

H-S distance, long vs medium, pt 2
5.0000 5.0000 0.0722 0.3281 3.7470 2.7760 1.1320 4.6840 0.0206

**COMPARISON OF H-S DISTANCE, POINT 3**

H-S distance, short vs long pt 3
5.0000 5.0000 0.0071 1.9195 3.1430 2.4470 1.9430 6.0589 0.7810

H-S distance, short vs medium, pt 3
5.0000 5.0000 0.0083 1.6979 2.8960 2.3650 1.8600 7.6233 0.6111

H-S distance, long vs medium, pt 3
5.0000 5.0000 0.0062 0.0029 2.9980 2.3650 1.8950 6.9287 0.3034

**COMPARISON OF H-S DISTANCE, POINT 2 VS POINT 3**

H-S distance, pt 2 vs pt 3
15.0000 15.0000 1.3239 13.1618 2.3080 2.0740 1.7170 21.8999 0.2359

H-S distance, pt 2 vs pt 3
15.0000 15.0000 3.3971 11.2800 2.4790 2.0560 1.7060 25.6253 0.6522

H-S distance, pt 2 vs pt 3
15.0000 15.0000 3.6292 12.3131 2.4670 2.0480 1.7010 27.6641 0.4449
### COMPARISON OF DRILL LENGTHS, POINT 2

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FIGURE F.180 Statistics on linear angles. LENGTH test, subject 8.
FIGURE F.181 Stick plots of upper limb; DRILL OFF test, subject 2.
FIGURE F.182 Averaged stick plots of upper limb; DRILL OFF test, subject 2.
FIGURE F.183 Stick plots of upper limb, DRILL OFF test, subject 3.
FIGURE F.184 Averaged stick plots of upper limb; DRILL OFF test, subject 3.
FIGURE F.185 Stick plots of upper limb; DRILL OFF test, subject 4.
FIGURE F.186  Averaged stick plots of upper limb, DRILL OFF test, subject 4.
FIGURE F.187 Stick plots of upper limb; DRILL OFF test, subject 5
FIGURE F.188  Averaged stick plots of upper limb, DRILL OFF test, subject 5.
FIGURE F.189 Stick plots of upper limb; DRILL OFF test, subject 6.
FIGURE F.190 Averaged stick plots of upper limb; DRILL OFF test, subject 6.
FIGURE F.191 Stick plots of upper limb; DRILL OFF test, subject 7.
FIGURE F.192 Averaged stick plots of upper limb, DRILL OFF test, subject 7.
FIGURE F.193 Stick plots of upper limb; DRILL OFF test, subject 8.
FIGURE F.194  Averaged stick plots of upper limb, DRILL OFF test, subject 8
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FIGURE F.196  Projected Grood&Suntay 3D angle, DRILL OFF test, subject 2
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FIGURE F.201 Grood & Suntay 3D angle, DRILL OFF test, subject 5.
FIGURE F.202 Projected Grood & Sunray 3D angle; DRILL OFF test, subject 5.
FIGURE F.203 Grood&Suntay 3D angle; DRILL OFF test, subject 6.
FIGURE F.204 Projected Grood & Suntay 3D angle; DRILL OFF test, subject 6.
FIGURE F.205 Grood & Suntay 3D angle; DRILL OFF test, subject 7.
FIGURE F.206 Projected Grood&Suntay 3D angle; DRILL OFF test, subject 7.
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FIGURE F.209 Linear angles; DRILL OFF test, subject 2.
This test was not performed with this subject.
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FIGURE F.212 Linear angles; DRILL OFF test, subject 5.
FIGURE F.213 Linear angles, DRILL OFF test, subject 6.
FIGURE F.214 Linear angles; DRILL OFF test, subject 7.
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FIGURE F.228 VTS, VTE, VTSVDR and VTEVDR angles; DRILL OFF test, subject 8.

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FIGURE F.229  VDRh, VDRv and EF angles; DRILL OFF test, subject 8.
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**H-S distance, off vs loc pt 1**

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**H-S distance, off vs loc pt 2**

- 5.0000 5.0000 0.0296 0.8058 2.9980 2.3650 1.8950 6.5770 0.7326

**H-S distance, off vs loc pt 3**

- 5.0000 5.0000 0.0313 0.2558 3.3650 2.5710 2.0150 4.8570 0.9022

**H-S distance, off vs loc pt 4**

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### COMPARISON DRILL OFF VS LOCATION, POINT 1

- **Wrist, off vs loc pt 1:**
  - n1: 5
  - n2: 5
  - s: 1.7660
  - equal: 1.6700
  - t: 2.0180
  - tref 2%: 5.1391
  - tref 5%: 0.1478

- **Elbow, off vs loc pt 1:**
  - n1: 5
  - n2: 5
  - s: 7.2012
  - equal: 7.1520
  - t: 2.3060
  - tref 2%: 1.1600
  - tref 5%: 7.5764

- **Shoulder, off vs loc pt 1:**
  - n1: 5
  - n2: 5
  - s: 0.0785
  - equal: 0.0703
  - t: 1.8990
  - tref 2%: 7.1456
  - tref 5%: 0.1271

### COMPARISON DRILL OFF VS LOCATION, POINT 2

- **Wrist, off vs loc pt 2:**
  - n1: 4
  - n2: 4
  - s: 1.8555
  - equal: 1.7644
  - t: 0.6241
  - tref 2%: 0.2222

- **Elbow, off vs loc pt 2:**
  - n1: 4
  - n2: 4
  - s: 4.8416
  - equal: 4.6874
  - t: 1.1820
  - tref 2%: 3.0341
  - tref 5%: 0.0057

- **Shoulder, off vs loc pt 2:**
  - n1: 4
  - n2: 4
  - s: 3.4948
  - equal: 3.4217
  - t: 2.7760
  - tref 2%: 3.3836
  - tref 5%: 0.1223

### COMPARISON DRILL OFF VS LOCATION, POINT 3

- **Wrist, off vs loc pt 3:**
  - n1: 5
  - n2: 5
  - s: 1.5491
  - equal: 1.4826
  - t: 1.9430
  - tref 2%: 5.8666
  - tref 5%: 0.8015

- **Elbow, off vs loc pt 3:**
  - n1: 5
  - n2: 5
  - s: 1.8122
  - equal: 1.7954
  - t: 2.3060
  - tref 2%: 1.6600
  - tref 5%: 7.9779

- **Shoulder, off vs loc pt 3:**
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  - n2: 5
  - s: 1.6020
  - equal: 1.3220
  - t: 2.3650
  - tref 2%: 1.9950
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### COMPARISON DRILL OFF VS LOCATION, POINT 4

- **Wrist, off vs loc pt 4:**
  - n1: 5
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  - s: 1.5160
  - equal: 1.3280
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  - tref 5%: 0.6571

- **Elbow, off vs loc pt 4:**
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  - s: 1.7417
  - equal: 1.7040
  - t: 1.8060
  - tref 2%: 1.8060
  - tref 5%: 7.9408

- **Shoulder, off vs loc pt 4:**
  - n1: 5
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  - s: 1.5467
  - equal: 1.3980
  - t: 1.8950
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### COMPARISON DRILL OFF VS LOCATION, POINT 4

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### COMPARISON DRILL OFF VS LOCATION, POINT 1 TO 4

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### COMPARISON DRILL OFF VS LOCATION, POINT 1

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### COMPARISON DRILL OFF VS LOCATION, POINT 4

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FIGURE F.237  Hand-Shoulder distance (H-S distance) for all subjects, for all four tests: LOCATION, FORCE, LENGTH and DRILL OF tests.
**FIGURE F.238** Subject 10, Medium stick, 50% force.

*Left plots:* Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

*Right plot:* Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 518
FIGURE F.239 Subject 10, Medium stick, 85% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (---) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 
FIGURE F.240 Subject 10, Long stick, 50% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (----) mean of experimental relative displacements of each sequence, (-----) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 520
FIGURE F.241 Subject 10, Long stick, 85% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (-----) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 521
FIGURE F.242 Subject 10, Long stick centered, 50% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 522
FIGURE F.243 Subject 10, Long stick, centered, 85% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (---) mean of experimental relative displacements of each sequence, (-----) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 523
FIGURE F.244 Subject 10, Long stick, location 2, 50% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (----) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 524
FIGURE F.245 Subject 11, Long stick, centered, 50% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (---) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 525
**FIGURE F.246** Subject 11, Long stick, 85% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 526
FIGURE F.247 Subject 11, Long stick, 65% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (——) mean of experimental relative displacements of each sequence, (----) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 527
FIGURE F.248 Subject 11, Long stick, 85% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (----) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 528
**Figure F.249** Subject 11, Medium stick, 65% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (---) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C'_{ps}$. 
FIGURE F.250 Subject 11, Medium stick, 50% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{px}$. 
**FIGURE F.251** Subject 13, Pulling, 50% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C'_{ps}$. 

*Page 531*
FIGURE F.252 Subject 13, Pulling 65% force.

Left plot: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (---) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C'ps$. 
**FIGURE F.253** Subject 13, Pulling, 85% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C'_{ps}$. 
FIGURE F.254  Subject 14, Long stick, centered, 85% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C^p$.
FIGURE F.255 Subject 14, Long stick, centered, MAX force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C^{ps}$. 

Page 535
FIGURE F.256 Subject 14, Long stick, centered, 50% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (---) mean of experimental relative displacements of each sequence, (--) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 
FIGURE F.257 Subject 15, Medium stick, 85% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain. Right plot: Comparison of linear model and experimental relative displacements. (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C'_{ps}$. 

Page 537
FIGURE F.258 Subject 15, Medium stick, 65% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs. (---) mean of experimental relative displacements of each sequence, (----) relative displacements due to same input forces, but based on linear compliance matrix $C_{p_s}$.
FIGURE F.259 Subject 15, Medium stick, 50% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 
FIGURE F.260 Subject 15, Long stick, 65% force.

**Left plots:** Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a 1N force input circular domain.

**Right plot:** Comparison of linear model and experimental relative displacements: (o) force inputs, (---) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 

Page 540
FIGURE F.261 Subject 15, Pulling, 65% force.

Left plots: Normalized relative displacements. Top plot: all displacements for all sequences. Bottom plot: mean of all displacements within a sequence of perturbations. Ellipsoids represent the linear compliance model fitted to the data, assuming a LN force input circular domain.

Right plot: Comparison of linear model and experimental relative displacements: (o) force inputs, (—) mean of experimental relative displacements of each sequence, (---) relative displacements due to same input forces, but based on linear compliance matrix $C_{ps}$. 