Analysis of Human Coordination Patterns between a Younger and Older Age Group during the Timed Up and Go Test

by

Danielle Barillas

Submitted to the
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ABSTRACT

An experimental study was performed to understand lower limb movement patterns between older and young adults, and to explore a new metric of coordination. Lower limb and torso movement in an older and younger population was captured using both IMU sensors and an optical tracking system. Only data from the optical method was processed and analyzed for this thesis. The participants executed several trials of a Timed-Up-and-Go test (TUGT), a 10 meter Walk Test (10MWT), and a Standing Balance Test (SBT). This paper specifically analyzed data from seven of the participants when executing the TUG test. The Relative Coordination Metric (RCM) from Hip to Knee and from Knee to Ankle was briefly explored for one subject from each age group. Several qualitative differences in motion were seen between the younger subject and the older subject for the Hip-Knee RCM, while similarities were identified for the Knee-Ankle RCM. The TUG time for the younger age group ($M = 11.48s$, $SD = 1.26s$) and the older age group ($M = 12.06s$, $SD = 0.69s$) was also compared and it was found that they were significantly different ($t = 1.998$, $p = 0.017$).

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1. Introduction

1.1 Motivation

The study of human coordination has many applications, especially in healthcare. Within healthcare, many studies have been dedicated towards assessing fall risk. Falls are the leading cause of injury for those above 65 years of age in the US [1]. One out of five falls results in serious injury, such as fractures or head injuries. The injuries negatively affect a person's independence by limiting their ability to perform activities of daily living. Some of the factors that contribute to a high fall risk are difficulties walking or problems with balance.

Injured individuals may be referred to physical therapists to contribute to their recovery. These professionals are qualified in assessing an individual's fall risk and can prescribe proper exercises that both contribute to the patient's recovery and evaluate the patient's quality of movement. There are several tests, like the Timed-Up-and-Go (TUGT), Sit-to-Stand (STS), and a One-Legged-Stance, that help assess a person's balance, gait, or overall motion [2]. However, it is difficult for the therapist to evaluate their patient's progress outside of the in-clinic therapy sessions. Metrics that provide clinicians with patient progress and quality of movement between therapy sessions will help clinicians overcome that obstacle.

This study focuses on observing lower limb biomechanics of healthy individuals to understand the differences in gait motion profiles between younger and older adults using a novel metric of coordination.

1.2 Coordination of Movement

Human coordination can be evaluated using a wide variety of methods that characterize motion through its velocities, forces, and even muscle behavior.

Velocity is frequently collected, especially in tests like the 10 meter Walk Test and its variations. Walking speed is used to measure functional mobility of clinical patients [3]. It can determine rehabilitation needs, future mobility functionality, as well as fall risk. Speed of human movement, overall, however, is also shown to affect the accuracy of movement. This phenomena is called the *speed-accuracy trade-off*. It describes how there may be a decrease in accuracy of a motion as the speed of that motion increases. The physiological cause for this is likely the variability of noise that exists in the neuro-mechanical system. The amount of noise in motor commands tend to increase with commands of higher magnitude [4]. Although speed can describe an individual's movement, additional metrics may applied to further understand coordination.

Time to complete a task can be one of the simplest ways of correlating human performance to health. Time to completion from various tasks, such as TUGT, is often correlated with other clinically relevant parameters, such as fall risk. Previous studies have used total time to complete an exercise as a method for assessing differences in limb motion between young and healthy elderly individuals [5].

One of the most common ways physical therapist or rehabilitation clinician receive information about a patient's quality of movement is through direct interaction or visual observation. During clinical visits, it is common for clinicians to evaluate the motion of particular limbs or joints, or even overall movements. These professionals are crucial in identifying irregularities in various motor control patterns such as gait, balance, and fall risk [6].

This paper will focus on utilizing the time to execute a task along with joint orientations and angular velocity of the hip, knee, and ankle to understand joint patterns between a younger and older age group. The Relative Coordination Metric (RCM) will be calculated using the joint angular velocities to quantify the coordination between two limb segments. This metric was applied in this study for an initial qualitative assessment on how it quantifies joint movement between younger and older adults.

1.3 Measurements for Fall Risk

There are several standard exercises that are used to characterize gait and fall risk. Two are the Time-Up-and-Go test (TUGT) and a 10 meter Walk Test (10MWT).

The TUGT involves beginning in a sitting position, walking 3 meters, and ending in a seated position. The TUGT and its subtasks are well associated with fall risk. It also can assess mobility, balance, and walking ability [6]. While the time to complete a TUGT is a well-established measurement to aid in describing fall risk, the interpretation of risk is not consistent and time may be affected by the instructions given. The average TUGT time varies across the literature; some are shown in Table 1.

In the table, it's seen how the TUGT times vary from each study. Bergmann's experiment specifically explored the how TUGT times vary depending on the instructions given. It was discovered that for both a young and old age group, verbal instructions affected TUGT times [9]. Shumway-Cook's experiment, for example, instructed participants to walk as quickly and safely as possible.

Table 1: Collection of Average TUGT Times

Study	Age Range (yrs)	Sample Size	Average TUGT Time*
Bischoff[7]	65-85	413	8.3s ± 1.9s
Shumway-Cook[8]	65-85	15	8.4s ± 1.7s
Bergmann[9]	60-76	14	8.75s
Medley & Thompson[10]	65-74	20	10.7s ± 1.9s
Iluz et all[11]	78.65 ± 4.35*	38	10.22s ± 2.53s
Daubney & Culham[10]	65-91	39	11.1s ± 3.7s
Hughes[10]	65-86	20	13.0s ± 2.6s
Iluz et all[11]	28.06 ± 3.99*	30	7.66s ± 1.96s
Bergmann[9]	19-25	14	9s

*Mean ± Standard Deviation

The 10MWT involves beginning in a standing position, walking 10 meters, and ending in a standing position. It's used to acquire gait speed, as well as time to complete the task. How fast or slow the individual travels can be used to predict any need of intervention to reduce probability of falling. Like the TUGT, thresholds between high and low fall risk vary. Harnish et al [6], for example, determined that a gait speed greater than 0.8m/s fell under a low fall risk. Normative gait speed for individuals between 20-79 years old are listed below:

*Table 2: Reports of Average Gait Speed[12]**

Age	Male Gait Speed (m/s)	Female Gait Speed (m/s)
20s	1.39	1.41
30s	1.46	1.42
40s	1.46	1.39
50s	1.39	1.40
60s	1.36	1.30
70s	1.33	1.27

*There were 230 participants. Gait speed was calculated over a distance of 7.62m.

Poor balance or balance disorders are also common causes of falls in the elderly population [13]. The SBT is usually applied in assessing an individual's balance. There are many versions of this test, such as standing with one leg off the ground for as long as possible without external support. A time standing in this manner for more than 30 seconds corresponds to a low fall risk. Another version is standing with both feet side by side, and then slightly staggered. From this version, the change in pressure along each foot, or postural sway can be extracted to characterize the balance of an individual [2].

1.4 Research Goals and Outline

The purpose of this study is to understand different joint movement patterns between younger and older adults when performing common physical therapy tasks for assessing fall risk and specifically whether a new metric for coordination (RCM) can be used to quantify performance while completing these tasks. This metric may further help clinicians characterize how a patient executes a task. To this end, the research questions of this study are:

1. Is there a statistically significant difference in the TUGT times between Older and Younger Adults with a total population of seven participants?
2. What can be inferred from the RCM between one young subject and one old subject that can be applied for further investigation?

This thesis paper will describe the experimental setup and procedure carried out by the participants, as well as explain the methods for data analysis. The results of the experiment will be presented and discussed, followed by a summary of the study's purpose and finding.

2. Methods

2.1 Experimental Design

Data was acquired from seven healthy individuals who participated in the experiment. Four of the participants ranged from 18-30 years of age (M = 22.25, SD = 0.96) and three participants were above the age of 60 (M = 67, SD = 3.46). Exclusion criterion included any neurological, blood, heart, or lung problems, surgeries done within six months of the experiment, and inability to perform tasks of the experiment without an assistive device. Each participant supplied a written informed consent and the protocol was approved by the MIT Committee of the Use of Human as Experimental Subjects. Each subject received up to $25 compensation for participating.

Each participant executed three distinct activities: 10MWT, a Standing Balance (SBT), and TUGT. The 10MWT involved walking along a path that was 10m long and the SBT involved standing straight with feet placed shoulder-width apart for 40 seconds. The TUGT initialized with the participant sitting on a stool, standing up, walking towards and around a marker, and ending with the participant seated on the stool. There were two 10MWT trials, 6 SBT trials, and 15 TUGT trials. One 10MWT and 3 SBT trials were performed before and after the 15 TUGT trials as a measure of any fatigue effects in this study. The first five trials of the TUGT were used as practice runs to reduce any test anxiety the participants may have experienced and were therefore not used for analysis.

The participants' movements were recorded using a 14-camera motion capture system (Bonita, VICON Inc., USA) at 100 Hz. A total of 48 reflective markers were placed along the legs, foot, torso, and head. Eight IMU sensors (APDM Opal) were strapped on the legs, waist, and chest. The placement for all markers and sensors are visualized in Figure 1.

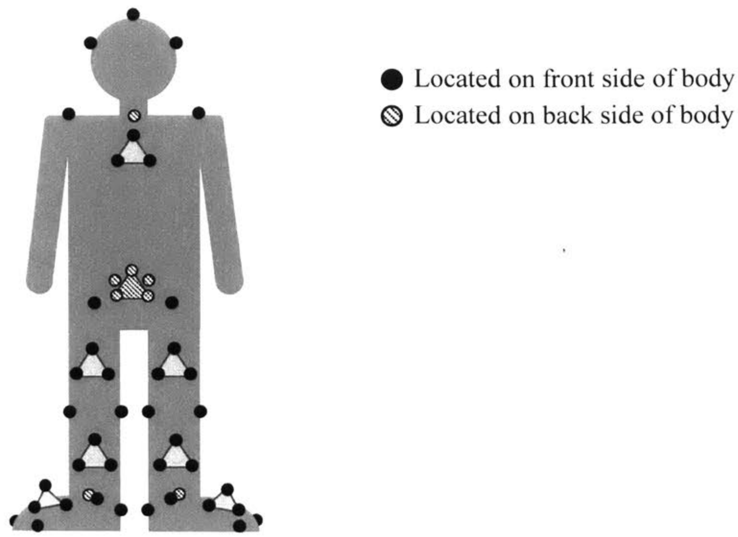

Figure 1: Marker and IMU Placement. Circles represent individual markers and white triangles represent IMU sensor.

For this study, the TUGT trials were analyzed using data acquired from the Vicon Camera system.

2.2 Data Processing

All marker trajectories were recorded using the Nexus Motion Capture Software 2.5. This data was later processed using OpenSim 3.3. Markers were placed using a modified Cleveland Clinic and Plug-in-Gait marker set [14]. The velocity of a Sternum marker was used to calculate the beginning and end of each trial. This marker was selected because it encapsulated different starting motion strategies, such as the subject leaning forward initially or the subject immediately beginning to stand in the vertical direction. The first frames of each trial when the subject was still were used to determine measurement noise within the system. The standard deviation (σ) of sternum velocity during these frames was calculated. The frame whose velocity was five times σ

was designated as the starting point. The same method was applied to determine the end time of the TUGT trial.

For the TUGT, the joint angles were extracted after applyin the inverse kinematics feature using OpenSim Model gait2354. The joint angles were used to calculate the angular velocity for the knees, hips, and angles of each trial. A 6th-order Butterworth filter (cutoff frequency of 10Hz) was applied to the joint angular velocities. The L^2- norm angular velocity was then calculated for the filtered joint angular velocities using the following equation:

$$\Omega_i(t) = \frac{\sqrt{\sum_1^N (\frac{\omega_n}{j_n})^2}}{N * J_t} \qquad [1]$$

where N is degrees of freedom of the limb, ω_n is the angular velocity of the joint axis n at some time t, j_N is a normalization parameter specific to the joint axis, and J_t is a normalization parameter for all joint axes. There are several normalization methods that affect the value of j_N and J_t. In this paper, the RCM was normalized by angular velocity, where j_N is the maximum angular velocity for the joint axis and J_t is 1. From this, the RCM (ρ_{12}) is defined as:

$$\rho_{12}(t) = 2\,tan^{-1}\left(\frac{\Omega_1(t)}{\Omega_2(t)}\right) - 90° \qquad [2]$$

The resulting RCM ranges from -90° to +90°, and is split into 4 zones. Zone 1 ranges from -20° to +20°, Zone 2 is from |20°| to |40°|, Zone 3 is from |40°| to |60°|, and Zone 4 is from |60°| to |90°|. Zone 1 indicates the highest level of coordination. If ρ_{12} is more than 0°, then segment 1 dominates motion between the two segments. If ρ_{12} is less than 0°, then segment 2 dominates motion [15].

The knee was defined to have 1 DoF, while the hip had 3 DoF and the ankle had 2 DoF. The RCM was calculated for the Right Hip-Right Knee pairing and the Right Knee- Right Ankle pairing for Subject 3 from the Young group and Subject 1 from the Older group.

2.3 Statistical Analysis

The TUGT total times were used for statistical analysis. The times from the Younger group and the Older group were compared and analyzed using a Two-Sample T-Test for Unequal Variance with an alpha of 0.05. The average total times for each subject were also compared graphically (Figure 2). The RCM calculations were presented graphically and interpreted by which zones were most occupied (Figure 5-7).

3. Results & Discussion

The data collected from the TUGT for each subject was processed and analyzed. The time to complete each task was calculated for each trial. Figure 2 is a box plot that illustrates the data set for each subject.

3.1 Total Time for TUGT

Using the information gathered from the trials, the mean and standard deviation for each subject were calculated.

Table 3: Subject Average TUGT Times

Subject	Mean (s)	Standard Deviation (s)
Subject Y1	12.99	1.03
Subject Y2	10.91	0.54
Subject Y3	10.43	0.71
Subject Y4	11.61	0.93
Subject O1	12.37	0.65
Subject O2	11.69	0.64
Subject O3	11.95	0.76

The overall average TUGT time for the younger age group was 11.48s ± 0.40s. The older group had a slightly higher average of 12.06s ± 0.26s. The average for the older group leans towards the higher side of the TUGT times listed in Table 1 and is similar to results reported by Hughes [8] and the Daubney & Culham [8]. The average for the younger age group is higher than the norms listed in Table 1. This difference from published norms is driven by the high TUGT average from Subject Y1.

By using the T-Test, it was found that the data support a difference in mean TUG between young and older groups ($t = 1.998$, $p = 0.017$). Here the older group had a significantly greater mean than the younger group, which is consistent with the literature.

As seen in Subject Y1's box in Figure 2, its overall median is the highest out of the subjects'. This may have been due to the level of fatigue the subject was experiencing prior to the experiment. For all subjects, it was instructed that they walk at a self-selected, comfortable pace, which may explain why the total TUGT times from all subjects are in the higher end of TUGT times reported in other studies (Table 1). This is also a small sample size, which means it may not be the best representative sample of the population.

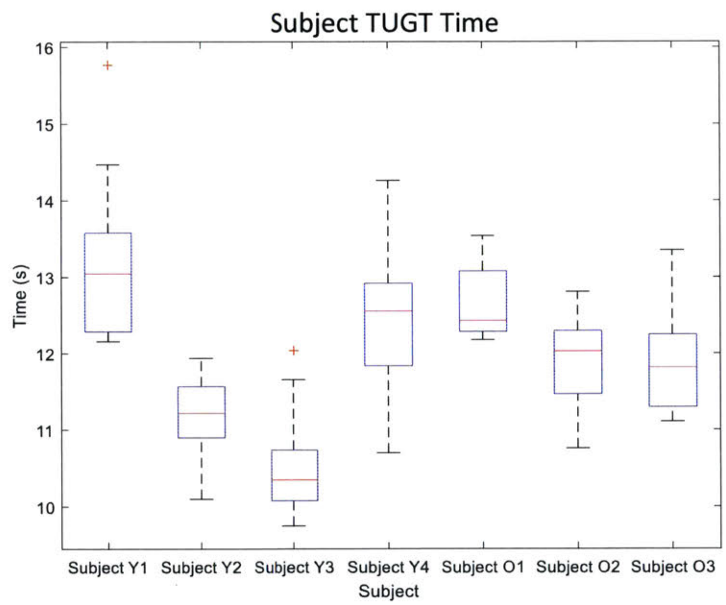

Figure 2: Box Plot of Subject TUGT Times. The red lines are the median values, the bottom and top blue lines are the lower to upper quartile range, encompassing 50% of the data. The black whiskers include data within 25%-75% of the data. Red crosses represent outliers.

It was previously noted that TUGT time fall risk vary. Here, all participants were below the 14 second fall risk threshold defined by Howcroft. This is expected since all subjects that participated were deemed healthy individuals.

3.2 Relative Coordination Metric between Two Subjects

As mentioned before, all participants walked at their own pace. Unlike time to complete the task, a performance metric can further characterize a subject's gait throughout the task. The RCM was calculated for one subject from each population, Subject Y3 and Subject O1. The right Hip-Knee and Knee-Ankle RCM for five trials was calculated for both subjects.

The joint angles were extracted from OpenSim for the time interval that encompassed the start and end of the TUGT movement. Figure 3 and 4 illustrate the progression of joint angles over time of a single trial for each subject.

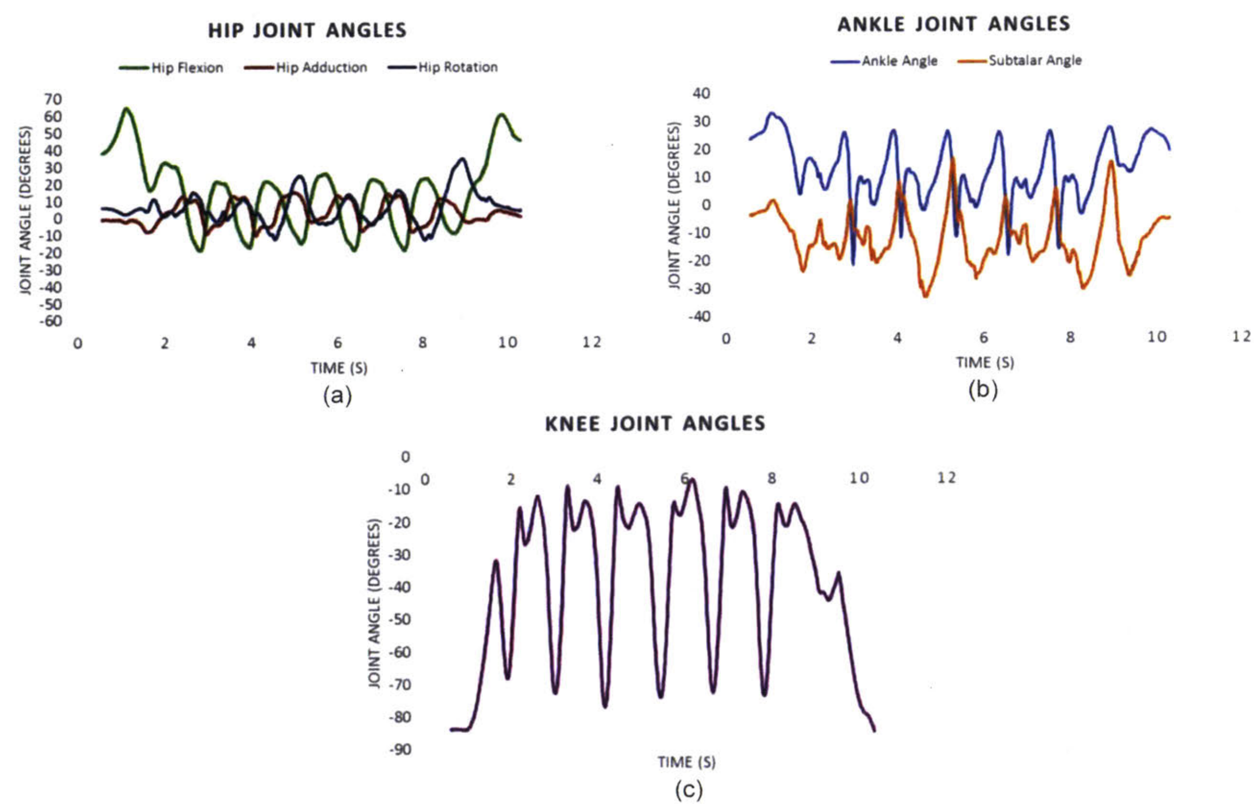

Figure 3: Hip, Ankle, and Knee Joint Angles for Subject Y3 for Trial 1. The hip has three rotational axes and therefore 3 DoF. The ankle has two rotational axes and DoF. The knee can only bend in along one axis, where 0° is the fully extended position.

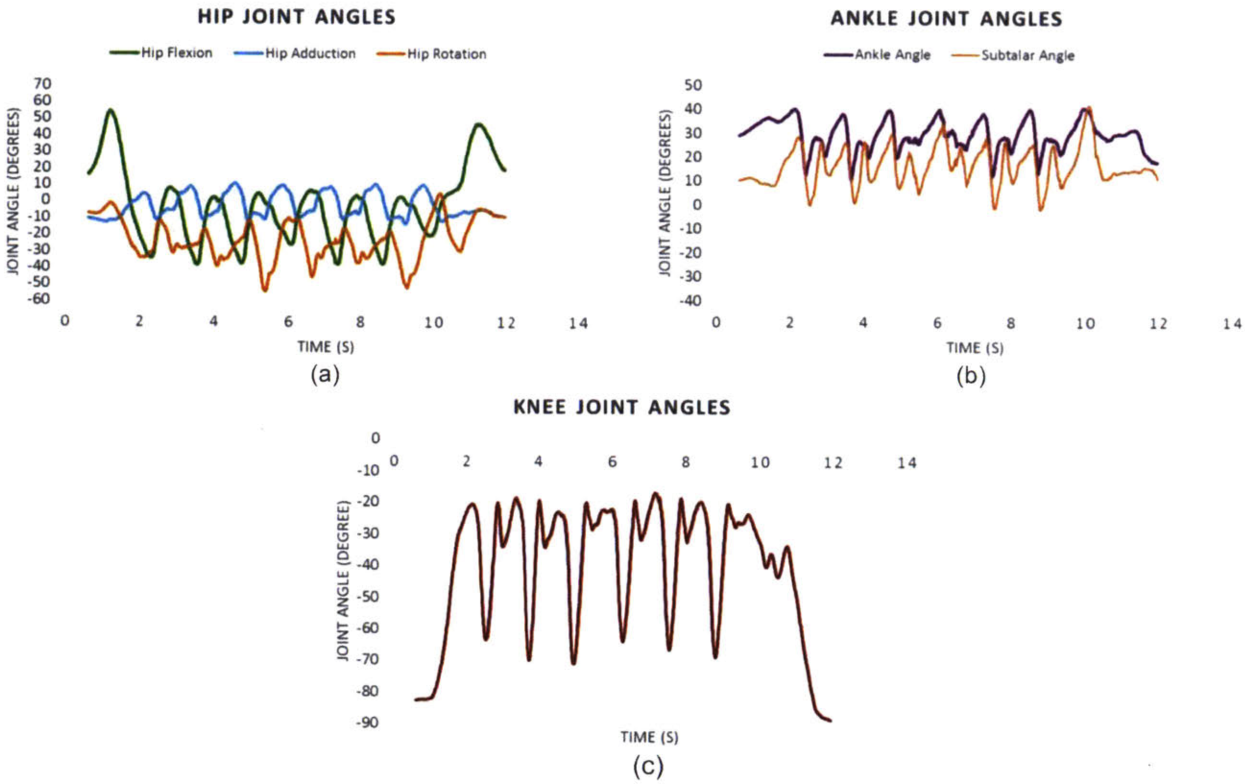

Figure 4: Hip, Ankle, and Knee Joint Angles for Subject O1 for Trial 1. The hip is split into three axes: flexion, adduction, and rotation. The ankle has two DoF as shown by the two lines. The knee's joint angle ranges from 90°, which was the starting and ending position, to 0°.

The two subjects show similar trends in joint angle movement over time, but there are some distinctions between the two. For example, the peaks in joint angles for the knee remain just around 20° for Subject O1, whereas Subject Y3's knee angle consistently exceeds 20°. Subject Y3 reached a fuller extension of the leg than Subject O1.

The hip joint angles also vary in each subject. Subject O1 has a larger range of motion in flexion and rotation of the hip, while Subject Y3 has a more constrained range. For hip flexion, both subjects had similar peak values, but Subject O1's motion flexes farther, to a value of -40°. For hip rotation, Subject Y3's hip rotation is limited between -20° and 20°, indicating normal use about that axis. Subject O1's hip rotation spans from 0° to -60° and appears centered below 0°.

The subject's larger motion about this axis may indicate that the toes were pointing away from the sagittal plane of the participant.

The joint angle progression was differentiated to obtain angular velocity over time of each joint's axes. Equation (1) was used to obtain normalized angular velocity. The use of equation (2) output the RCM over time. These results of a single trial are illustrated in Figure 5 and Figure 6.

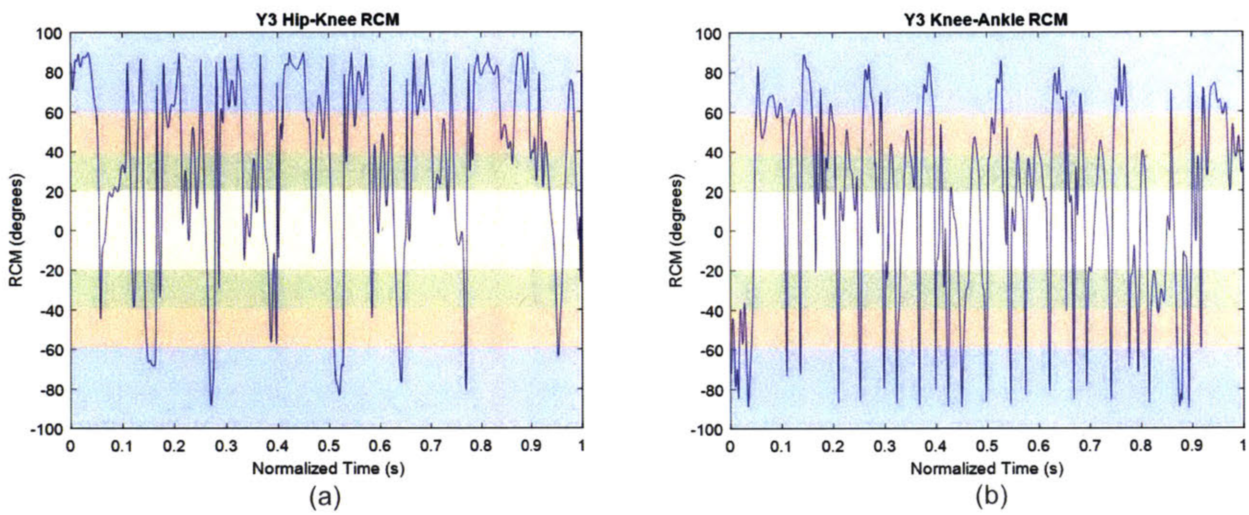

Figure 5: Hip-Knee RCM (a) and Knee-Ankle RCM (b) for Subject Y3. Yellow corresponds to Zone 1, green to Zone 2, orange to Zone 3, and blue to Zone 4.

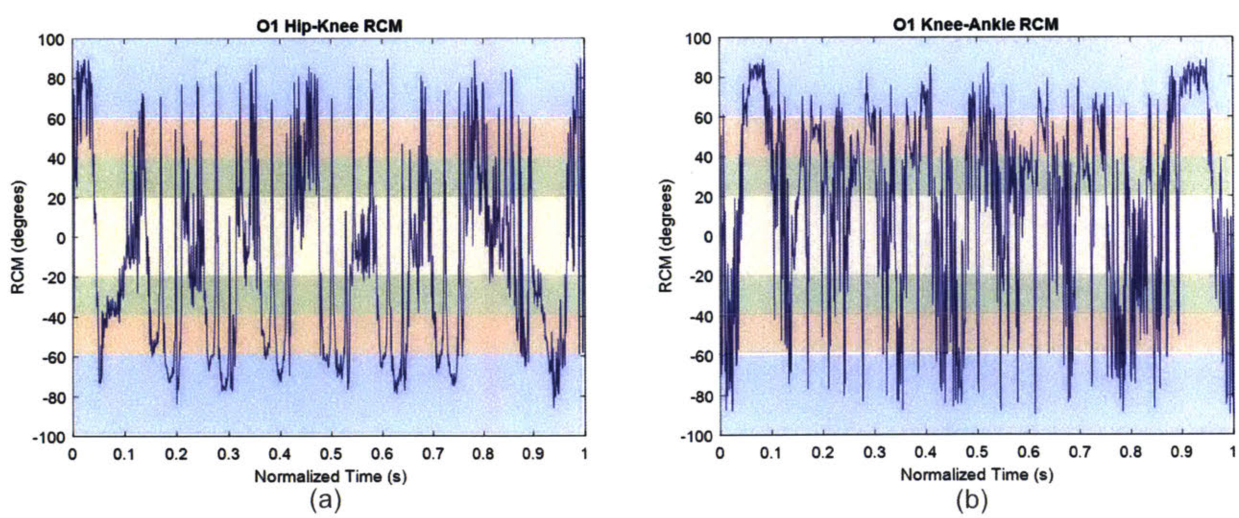

Figure 6: Hip-Knee RCM (a) and Knee-Ankle RCM (b) for Subject O1.

The graphs above are normalized over time so that it ranges from 0 to 1. Due to the DoF normalization used in Equation (1), the RCM results may be skewed away from the hip or ankle which have more DoF than the knee. Normalizing by degrees of freedom for joint axes that have smaller ranges of motion could be overcorrections, therefore skewing this RCM data slightly. These data are interpreted considering this potential limitation. A statistical analysis was not performed for the RCM results, and were instead interpreted qualitatively.

For Hip-Knee, it appears that Subject Y3 enters +Zone 4 more than in Subject O1. This indicates a more dominant use of the hip in this motion for Subject Y3 for this trial. For Knee-Ankle, it appears that both subjects have very similar behavior, both favoring +Zone 4, corresponding to more knee usage.

Five trials from each subject were used to calculate the RCM zones for Hip-Knee and Knee-Ankle pairings. Figure 7 illustrates the how often a subject remained in each zone across all five trials.

The zone frequency for Hip-Knee RCM differs quite noticeably between the younger and older subject. The hip dominates motion for Subject Y3. Each trial reported a frequency between 64% and 69% for an RCM between +Z2 and +Z4. There was a very low overall frequency for the negative zones. There are hardly any points in time that reach –Z4, which would have indicated any instances of significant knee dominated motion. It also reports a moderate median frequency of around 22% in Z1.

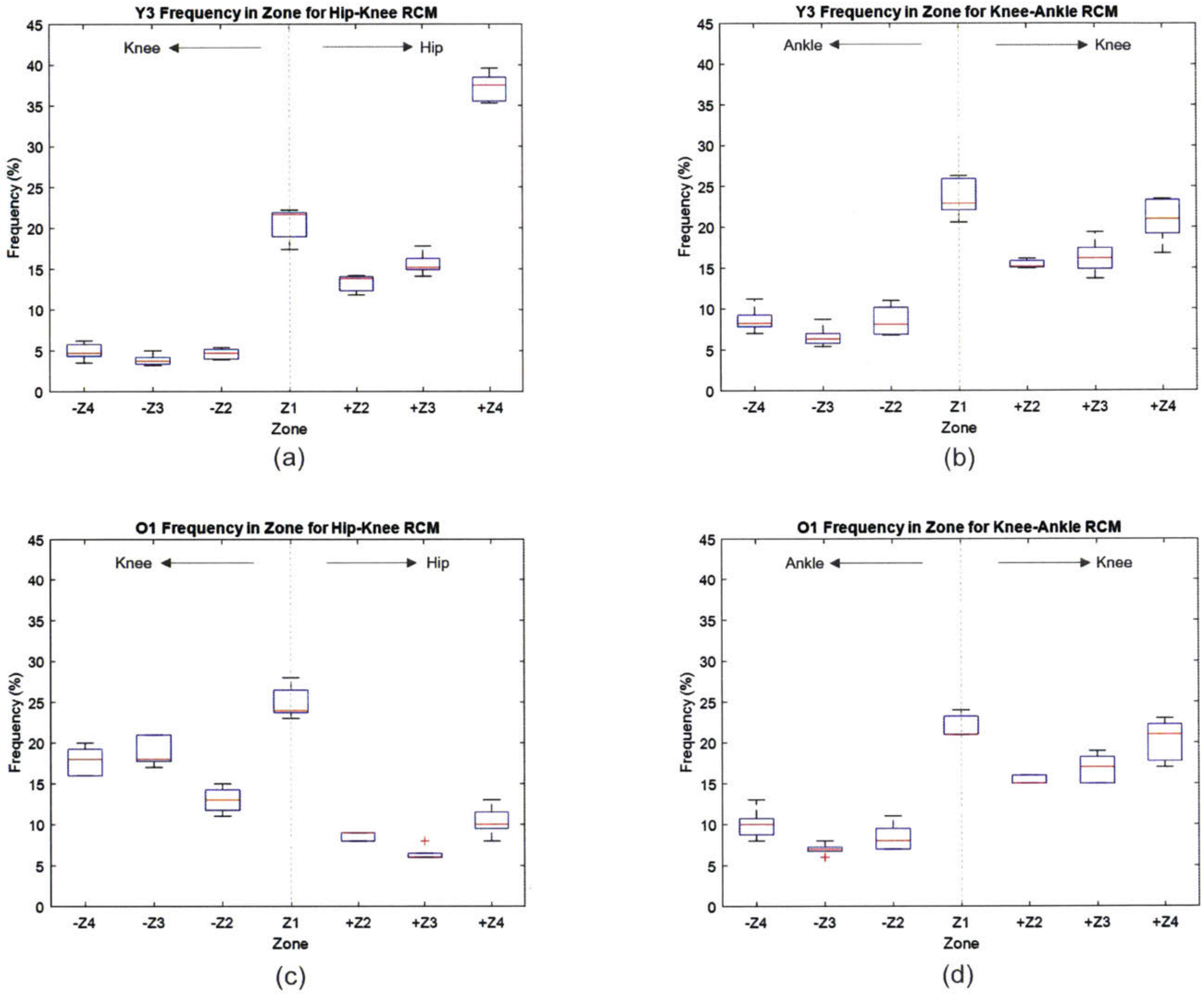

Figure 7: RCM Zone Boxplot. Each box represent the percentage of time the RCM was in a specific zone over five trials. The dotted line divides the plots into whichever joint dominates motion in that half. Plot (a) describes the RCM Hip-Knee for Subject Y3, Plot (b) describes the RCM Knee-Ankle for Subject Y3, Plot(c) describes the RCM Hip-Knee for Subject O1, and Plot (d) describes the RCM Knee-Ankle for Subject O1.

The plot for Subject O1 contrasts these outcomes. Rather than being dominated towards the hip, coordinated motion is more dominated towards the knee. It also has more instances that reach –Z4 compared to +Z4. The amount of time spent in the negative zones ranges from 49% to 56%.

Both subjects seemed equally coordinated for the Knee-Ankle RCM. Subject Y3 had a median of 23% in Z1, while Subject O1 had a slightly lower value of 21%. Overall, both appear to have a knee-dominated motion. Both subjects' RCM were between +Z2 and +Z4 for about twice the amount of time than in the negative zones. Future work will more closely evaluate the progression of RCM over time for more subjects and RCM pairings, as well as understand the effects of different RCM normalization schemes.

4. Conclusion

This paper focused on observing joint patterns and coordination differences between older and younger adults when doing a TUGT. The TUGT incorporates aspects of balance, gait speed, and lower limb coordination. It is also fitting in determining an individual's fall risk. The TUGT times were extracted from each subject and were found to be consistent with other TUGT studies (Table 1). The TUGT times each subject were used to determine a significant statistical difference between the two age groups. The RCM for two subjects from each age group was also calculated and observed over the time it took to complete a TUGT. Several differences in RCM values between an older subject and a younger subject were seen. Future work will explore RCM outcomes on different physical tasks and on a larger subject population.

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