Supernumerary Robotic Limbs for Next Generation Space Suit Technology

by

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Abstract

Extra-Vehicular Activities (EVAs) are considered one of the most complex operations an astronaut can perform during a spaceflight mission. Coordinating and executing EVAs are complex and costly affairs that are a necessity for any space vehicle; this is especially true for expanding the longevity of a spacecraft, like that of the International Space Station (ISS). A key challenge in planning EVAs is the amount of time an astronaut has to complete a series of tasks, which is inversely related to their metabolic load. Prior studies have determined that the bio-mechanics of a space suit wearing astronaut play a significant role in their metabolic load. In addition to this concern, another key challenge for astronauts conducting EVAs is to have access to a rigid tether to enable them full access to both of their arms when conducting a specific task. We propose the incorporation of a pair of wearable robots, called Supernumerary Robotic Limbs (SuperLimbs), which would be mounted on the xEMU's Square Boss Interface (SBI), positioned such that each SuperLimb is on either side of the astronaut's center of mass. The use of SuperLimbs during an EVA allows the astronaut to safely and efficiently move across a spacecraft in EVA. The SuperLimbs grab EVA handrails for securing the astronaut's body, and guide the astronaut from one work location to another (thus reducing their overall work load). The incorporation of SuperLimbs onto the xEMU spacesuit forms a cooperative human-robotic system that can be modeled as a quadruped with two human arms and two SuperLimb grippers. Trajectory planning and control algorithms are developed as a quadrupedal locomotion problem, where the SuperLimbs act as followers while the astronaut operator is the leader. Furthermore, the quadruped human-robot system enables multiple points of contact at any point in the EVA, creating a secure bracing condition for the astronaut user that enhances both stability and controllability.

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Acknowledgments

I would like to thank my mom, who has supported me throughout my lifetime of hardships and successes. She has (and continues to be) my greatest champion as I move forward with life. I can confidently say that without question, my mom has helped forge me into the best version of myself I can possibly be, and with that, I am forever and eternally thankful.

In addition, I would also like to thank my family and friends back home, who have supported me since day one on this perilous journey. Without them, I could not have managed to navigate the loneliness that graduate school presents, especially when you travel to a part of the country you have no friends nor connections within.

Finally, I would like to thank my fellow lab mates in the d'Arbeloff Laboratory. With how much we chatted, laughed, cried, and chanted, I believe it's safe to say that you all too, belong in my list of eternal friends as well.

Get a good idea and stay with it. Dog it and work at it until it's done, and done right.
– Walter Elias Disney

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Chapter 1

Introduction

1.1 Motivation

Extra-Vehicular Activities (EVAs) are a necessary and complex operation undertaken during any spaceflight mission. Often times, space vehicles require maintenance or specialized experiments that force Astronauts to don a space suit and exit the safety of their habitat. Astronauts place themselves within an extreme environment and must work within a pressurized space suit to complete often difficult tasks [1]. Despite extensive efforts at NASA, it has been a challenge to fully mitigate the risks associated with EVAs, reduce the workload of astronauts, and improve productivity. To quantify the ergonomics of an astronaut within a space suit, key metrics are defined. According to [18], the human factors metrics associated with the space suit can be categorized by assessing both the torque-displacement of joints and kinematics of the astronaut's appendages during a worksite task. This assessment yields four key metrics: Range of Motion, Suited Strength, Reach Envelope, and Work Envelope. In general, astronauts carry around a foot-restraint which they rigidly fixate to a spacecraft's external structure to gain use of both arms, but severely limits their available work envelope [13]. Alternatively, the use of the Space Station Remote Manipulator System (SSRMS) can be used to manipulate the astronaut's position over a worksite, but is often cumbersome and introduces significant reliability and safety risks [2]. This paper proposes the use of a robotic system attached to the space suit of an astronaut for improving the ergonomics and capabilities of astronauts during EVA operations.

1.2 Prior Research

Supernumerary Robotic Limbs, or SuperLimbs for short, area a type of wearable robots attached to the body of a human [16], [20], [3]. Prior work on SuperLimbs has levitated towards applications in supporting a human operator subjected to gravitation effects, such as personnel in the construction and agricultural industries for improved worksite ergonomics [20], [9], [5]. These applications focus primarily on static posturing, where impedance and position control policies are enforced. However, working conditions in micro-gravity environments require the use of SuperLimbs to provide effective bracing that can be maintained while the user is in motion with minimal oversight [10]. A control policy, such as admittance control, has been shown to be an effective user interface when the operator is required to perform manipulation tasks [6], [8].

1.3 Proposed Solution

We propose to incorporate SuperLimbs into a space suit so that an astronaut can possess additional appendages, such as a third arm and a fourth leg. These SuperLimbs work in coordination with the astronaut as a portable rigid tether as well as a collaborative assistant in various EVA operations. For astronauts working on the ground for planetary explorations, the SuperLimbs can provide them with standing/lifting support, fall protection, incapacitated rescue operations, etc. For the initial development of this system, we look at EVAs conducted in micro-gravity environments, like that of the International Space Station (ISS). SuperLimbs attached to a space suit will allow the astronaut to move across the outside of the spacecraft, reposition the body, and secure it against a handrail or other fixtures on the spacecraft. The astronauts can use both hands for executing a mission task, rather than using one hand or both to

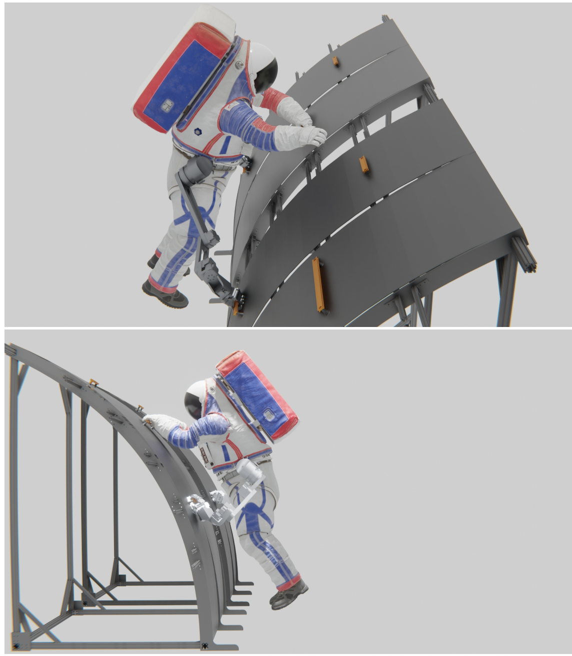


Figure 1-1: Space Suit SuperLimbs System Concept.

secure the body. This would improve the productivity of EVA operations and reduce the astronaut workload and, thereby, reduce energy consumption.

In the following discussion, a novel design concept of SuperLimbs incorporated into a space suit will be presented. A control algorithm, based on Admittance Control [15], [7], will be developed for assisting an astronaut in repositioning the body and securing the body despite disturbing loads. To validate the proposed design and control method, we developed a full-scale functional prototype of the Space Suit SuperLimbs system with a suspended testing environment to simulate micro-gravity EVA operations. With this prototype, we incorporated the Admittance Control Synthesis Scheme (ACSS), and evaluated the claims made in this discussion.

Chapter 2

Design Concept

Fig. $1-1$ shows a schematic of Space Suit SuperLimbs attached to a space suit. A pair of robot arms are placed around the waist and secured to the base frame of the space suit [17]. Each SuperLimb has a gripper that can securely grab a handrail [10] or other fixtures outside a space vehicle.

Two SuperLimbs are used for:

1. Securely bracing the astronaut body and the space suit; a single SuperLimb forms merely an open-kinematic chain, which is limited in structural strength and load bearing capacity.

2. Securely moving across the outside surface of a space vehicle, so that at least one SuperLimb is at all times grabbing a handrail including transitions from one handrail to another.

Each SuperLimb has a 6-axis force-torque sensor embedded in its end-effector, or at the wrist joint where a gripper is mounted. The two wrist force sensors measure the force and moment acting between the SuperLimbs and the handrail fixtures being grasped by the SuperLimbs. As the astronaut performs an EVA task, he/she interacts with the space vehicle's exterior structure. These interactions can be monitored with the two 6-axis wrist force sensors. The Space Suit SuperLimbs can assist an astronaut in many ways. Specifically, the current work addresses the following two major functions for micro-gravity EVAs.

Tethering and bracing anywhere - When an astronaut is positioned over a worksite, the SuperLimbs allows the astronaut to use both hands for executing a task and does so at a posture that is ergonomically effective and comfortable for the astronaut. Current state-of-the-art practices employ the use of a foot-restraint that can be installed at predetermined mounting locations on the external structure of the ISS or at the end-effector of the SSRMS. This practice results in mission planners having to meticulously design a task to be within an astronaut's work envelope to mitigate work postures susceptible to high safety risks [18]. In other cases, these foot-restraints cannot be used, and the astronauts must statically brace themselves with one of their arms [12]. A pair of SuperLimbs provide the astronaut with a fully rigid and adjustable tether anywhere during an EVA. This allows not only mission planners more flexibility in task design for EVAs, but it also allows astronauts to define their own comfortable worksite posture for a given task and the ability to carry out that task with use of both hands.

Inertial Mass Reduction - During a micro-gravity EVA, astronauts must transfer themselves from one location to another in order to reach target worksites or the airlock. These transfer operations are conducted primarily by the astronaut applying a load to an external structure to generate propulsion. The astronaut must push or pull the entire inertia of his/her body and the space suit. In case the astronaut must reposition his/her body frequently it may be more energy consuming. Furthermore, in case of emergencies and instances where a quicker transfer is required, astronauts run the risk of creating high joint torques which consequentially results in high metabolic loading that presents a significant safety risk [1], [14].

With a pair of SuperLimbs assisting the astronaut's movements, the SuperLimbs can virtually reduce the overall effective inertia of the astronaut and space suit, as to be later discussed. This enables the astronaut to exert smaller joint torques to achieve higher velocity transfers, thus mitigating high energetic consumption.

2.1 Constraints/Requirements Analysis

In this section, as with any well-developed engineering system, a set of constraints and requirements are defined based off industry-related data within both aerospace and robotics.

2.1.1 Pose Constraints/Requirements

With any manipulator design, it is imperative that the pose never places the joints into singularity configurations. This can cause solution errors with the inverse kinematic solvers on-board any manipulator platform [11]. Typically, this is averted by either

- Never allowing the motion plan of a manipulator to approach a singularity configuration or
- Utilizing a forced solver that captures the historical trend of the manipulator motion to solve past the singularity configuration

Provided this design constraint, the following requirements are to be made:

- The Space Suit SuperLimbs system shall have no joints (in static pose) be at 180°
  - The Space Suit SuperLimbs shall maintain a pose that forces each joint to be at least 15° from 180°
- The Space Suit SuperLimbs system shall at no point have either of the joints within the SuperLimbs be in singularity

2.1.2 Proximity Constraints/Requirements

Within a close-proximity to another spacecraft structure, it is critical that for the safety of both the astronaut and the spacecraft, that the two do not impact each other. This can cause potentially detrimental effects on spaceflight assets and personnel. Provided this constraint, the following requirements are to be set:

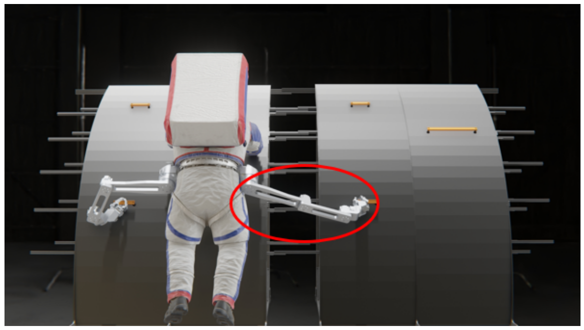


Figure 2-1: Singularity of SuperLimbs (circled in red).

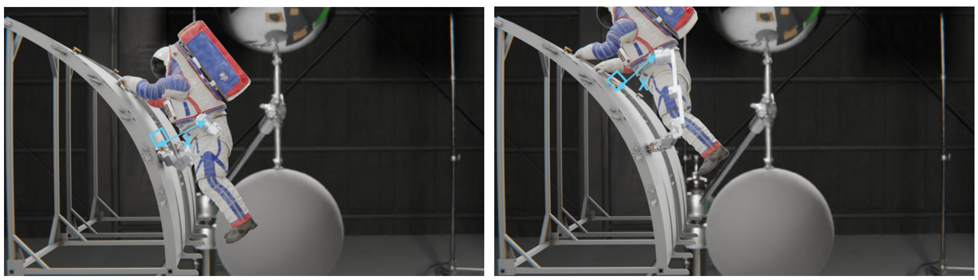


Figure 2-2: Proximity of astronaut CoM from spacecraft surface.

- The astronaut center of mass shall be X m (arbitrarily set based on EVA requirements) from the surface of the spacecraft that he/she is working upon
  - The astronaut is however allowed to adjust their relative distance from the surface they are working upon
- The astronaut's orientation with respect to the surface of the spacecraft shall be maintained and not change over time
  - The astronaut is however allowed to adjust their orientation from the surface they are working upon

2.1.3 Human-Volume Constraints

In the field of collaborative robotics, one area of concern is the close interaction of a robotic system with a human collaborator. Unintentional impacts from a manipulator on the human collaborator can cause potentially catastrophic injury and/or death.

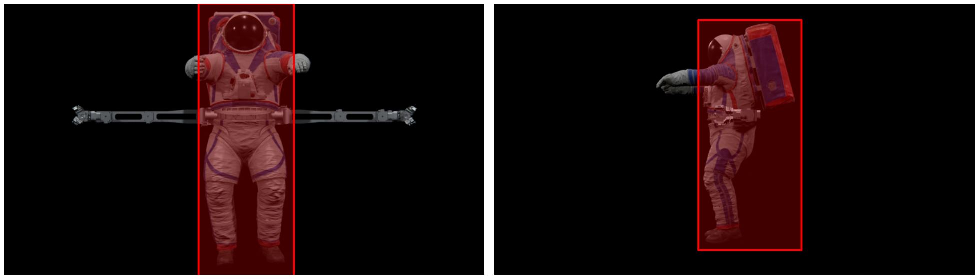


Figure 2-3: Keep out zone - Astronaut body volume (shown in red).

To avert this, the volume of the available manipulator workspace that contains the body of the astronaut is excluded. Therefore, the following requirement is made:

- No component of the SuperLimbs shall have the capability of striking the astronaut user

2.1.4 Human-Arm Constraints

Similar to the Human-Volume Constraints, the astronaut bears a reach envelope, as defined by [18] that must remain free from the SuperLimbs for the safety of the astronaut. Therefore, the following requirement is made:

- No component of the SuperLimbs shall have the capability of interfering with the astronaut's reach envelope

2.1.5 Environment Constraints

In addition to protecting the astronaut user from the manipulators, so too does the spacecraft they are interacting with. Therefore, the Space Suit SuperLimbs system contains the following requirement:

- No component of the SuperLimbs shall contain a solution (whether static or in motion) which contacts/extends beyond the boundary of the surface of the object for which it is interacting with

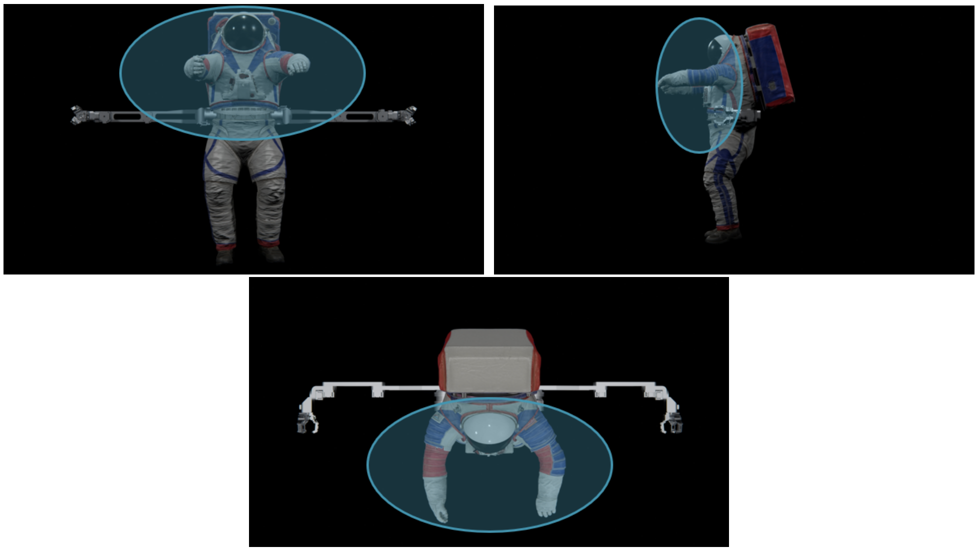


Figure 2-4: Keep out zone - Astronaut reach envelope (shown in blue).

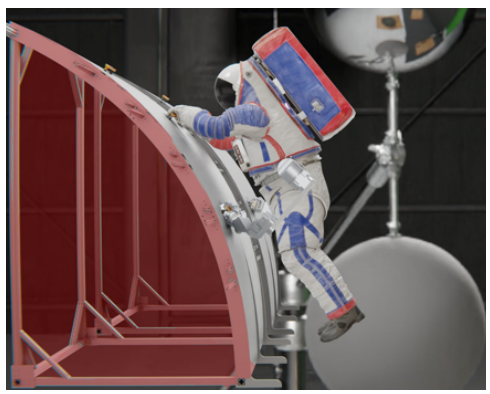


Figure 2-5: Keep out zone - Spacecraft volume (shown in red).

2.1.6 Torque/Performance Constraints/Requirements

The energetics contained within the SuperLimbs must also be factored into the design of the Space Suit SuperLimbs system. A robotic platform that bears the ability to deliver damaging/possibly lethal loads into any spaceflight asset must be averted. Therefore, the following requirements are made:

- The SuperLimbs shall not be in a configuration that requires any of its motors to exceed the maximum allowable torque (given a factor of safety (FOS) of 1.25)
- The SuperLimbs motor torques shall not exert torques capable of damaging either the astronaut user or any external objects

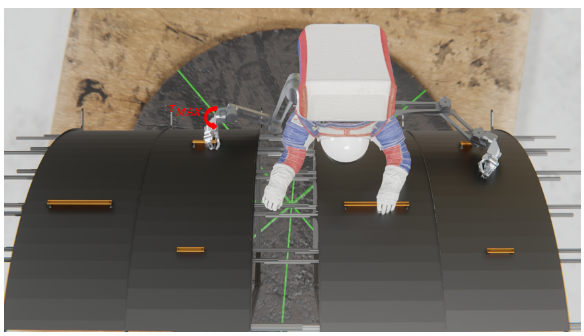


Figure 2-6: Maximum torque vector (at the wrist joint of the SuperLimbs).

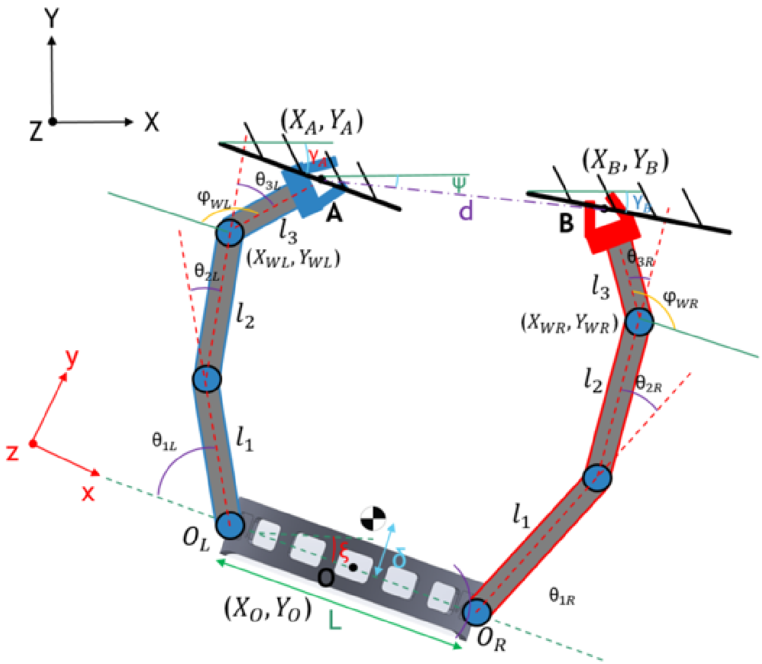


Figure 3-1: Generalized 2D Model of Space Suit SuperLimbs.

Chapter 3

Kinematics

3.1 Generalized 2-D Model

We can define the Space Suit SuperLimbs system in three coordinate frames: the astronaut body frame $O_h - X_h Y_h \gamma_h$, and the task space frames tied at the right $O_R - X_R Y_R \gamma_R$ and left $O_L - X_L Y_L \gamma_L$ end-effectors.

Suppose that the end-effectors of the two SuperLimbs are rigidly fixated to handlebars on the exterior surface of a space habitatation module separated by a distance d with orientation angle Ψ. Additionally, let's assume that the base of each SuperLimb is rigidly fixed to each end of the SBI along the astronaut's frontal plane with a prescribed length L. For the sake of simplicity, let's also assume that each SuperLimb is a 3-bar linkage that can only actuate along the XY plane.

Provided this, one can observe that the Space Suit SuperLimbs system is merely a closed-loop kinematic chain. With that understanding, lets express both d and Ψ as

$$d = d_x \hat{e_X} + d_y \hat{e_Y} \tag{3.1}$$

$$\Psi = \tan^{-1}[\frac{d_y}{d_x}] \tag{3.2}$$

3.1.1 Forward Kinematics (FK) Derivation

Solving the forward kinematics of each end-effector position and orientation with respect to O_h

$$\begin{aligned}
X_R = \frac{L}{2} + l_1\cos(\theta_{1R}) + l_2\cos(\theta_{1R}+\theta_{2R}) + l_3\cos(\theta_{1R}+\theta_{2R}+\theta_{3R}) \\
Y_R = l_1\sin(\theta_{1R}) + l_2\sin(\theta_{1R}+\theta_{2R}) + l_3\sin(\theta_{1R}+\theta_{2R}+\theta_{3R}) \\
\gamma_R = \theta_{1R}+\theta_{2R}+\theta_{3R} \\
X_L = -\frac{L}{2} - l_1\cos(\theta_{1L}) - l_2\cos(\theta_{1L}+\theta_{2L}) - l_3\cos(\theta_{1L}+\theta_{2L}+\theta_{3L}) \\
Y_L = l_1\sin(\theta_{1L}) + l_2\sin(\theta_{1L}+\theta_{2L}) + l_3\sin(\theta_{1L}+\theta_{2L}+\theta_{3L}) \\
\gamma_L = \pi - \theta_{1L}-\theta_{2L}-\theta_{3L}
\end{aligned}$$

3.1.2 Inverse Kinematics (IK) Derivation

Conversely, the Inverse Kinematics of this system can be determined if information about the position and orientation of the wrist joints is provided for each SuperLimb (given by $X_{WR}Y_{WR}\varphi_{WR}$ and $X_{WL}Y_{WL}\varphi_{WL}$ for the right and left SuperLimbs, respectively).

$$\theta_{1R} = \tan^{-1}[\frac{Y_{WR}}{X_{WR}}] - \cos^{-1}[\frac{(X_{WR} - \frac{L}{2}\cos\gamma_h)^2 + (Y_{WR} + \frac{L}{2}\sin\gamma_h)^2 + l_1^2 - l_2^2}{2l_1\sqrt{(X_{WR} - \frac{L}{2}\cos\gamma_h)^2 + (Y_{WR} + \frac{L}{2}\sin\gamma_h)^2}}]$$

$$\theta_{1L} = \tan^{-1}[\frac{Y_{WL}}{X_{WL}}] - \cos^{-1}[\frac{(X_{WL} - \frac{L}{2}\cos\gamma_h)^2 + (Y_{WL} - \frac{L}{2}\sin\gamma_h)^2 + l_1^2 - l_2^2}{2l_1\sqrt{(X_{WL} - \frac{L}{2}\cos\gamma_h)^2 + (Y_{WL} - \frac{L}{2}\sin\gamma_h)^2}}]$$

$$\theta_{2R} = \pi - \cos^{-1}[\frac{l_1^2 + l_2^2 - (X_{WR} - \frac{L}{2}\cos\gamma_h)^2 + (Y_{WR} + \frac{L}{2}\sin\gamma_h)^2}{2l_1l_2}]$$

$$\theta_{2L} = \pi - \cos^{-1}[\frac{l_1^2 + l_2^2 - (X_{WL} - \frac{L}{2}\cos\gamma_h)^2 + (Y_{WL} - \frac{L}{2}\sin\gamma_h)^2}{2l_1l_2}]$$

To find θ_{3R} and θ_{3L}, lets define a set of constraint equations for the closed-loop kinematic chain by solving the FK of the left end-effector from the base of the left SuperLimb in both the clockwise and counter-clockwise directions.

$$X_L = -[l_1\cos\theta_{1R} + l_2\cos\theta_{1R} + \theta_{2R} + l_3\cos\theta_{1R} + \theta_{2R} + \theta_{3R}] - L \quad (3.3)$$

$$X_L = l_1\cos\theta_{1L} + l_2\cos\theta_{1L} + \theta_{2L} + l_3\cos\theta_{1L} + \theta_{2L} + \theta_{3L} - d_x \quad (3.4)$$

$$Y_L = l_1\sin\theta_{1R} + l_2\sin\theta_{1R} + \theta_{2R} + l_3\sin\theta_{1R} + \theta_{2R} + \theta_{3R} \quad (3.5)$$

$$Y_L = l_1\sin\theta_{1L} + l_2\sin\theta_{1L} + \theta_{2L} + l_3\sin\theta_{1L} + \theta_{2L} + \theta_{3L} + d_y \quad (3.6)$$

Setting each pair of constraint equations equal to each other, one can find a closed-form solution for θ_{3R} and θ_{3L}.

$$\theta_{3R} = \frac{\cos^{-1} k_1 - \sin^{-1} k_2}{2} - \theta_{1R} - \theta_{2R}$$
$$\theta_{3L} = \frac{\cos^{-1} k_1 - \sin^{-1} k_2}{2} - \theta_{1L} - \theta_{2L}$$

where

$$k_1 = \frac{d_x - l_1 \cos(\theta_{1L}) + l_1 \cos(\theta_{1R}) + l_2 \cos(\theta_{1L} + \theta_{2L}) + l_2 \cos(\theta_{1R} + \theta_{2R}) - L}{l_3}$$
$$k_2 = \frac{-l_1 \sin(\theta_{1L}) + l_1 \sin(\theta_{1R}) - l_2 \sin(\theta_{1L} + \theta_{2L}) + l_2 \sin(\theta_{1R} + \theta_{2R}) - d_y}{l_3}$$

3.1.3 Jacobian Analysis

The relative velocities of the end-effectors can be expressed as $\dot{P} \in R^6$ and the relative joint velocities as $\dot{q} \in R^6$. Therefore, $J \in R^6$ is the Jacobian of the 2-D Space Suit SuperLimbs system.

Due to the closed-loop kinematic chain of the Space Suit SuperLimbs system, it comes as no surprise that the system is over-actuated. Since two constraint equations were defined that enabled solving for θ_{3R} and θ_{3L}, the following statement can be made:

$$rank(J) = 4$$
$$dim_{null}(J) = 2$$

This claims that the closed-loop kinematic chain contains two redundant DoFs, which are θ_{3R} and θ_{3L}.

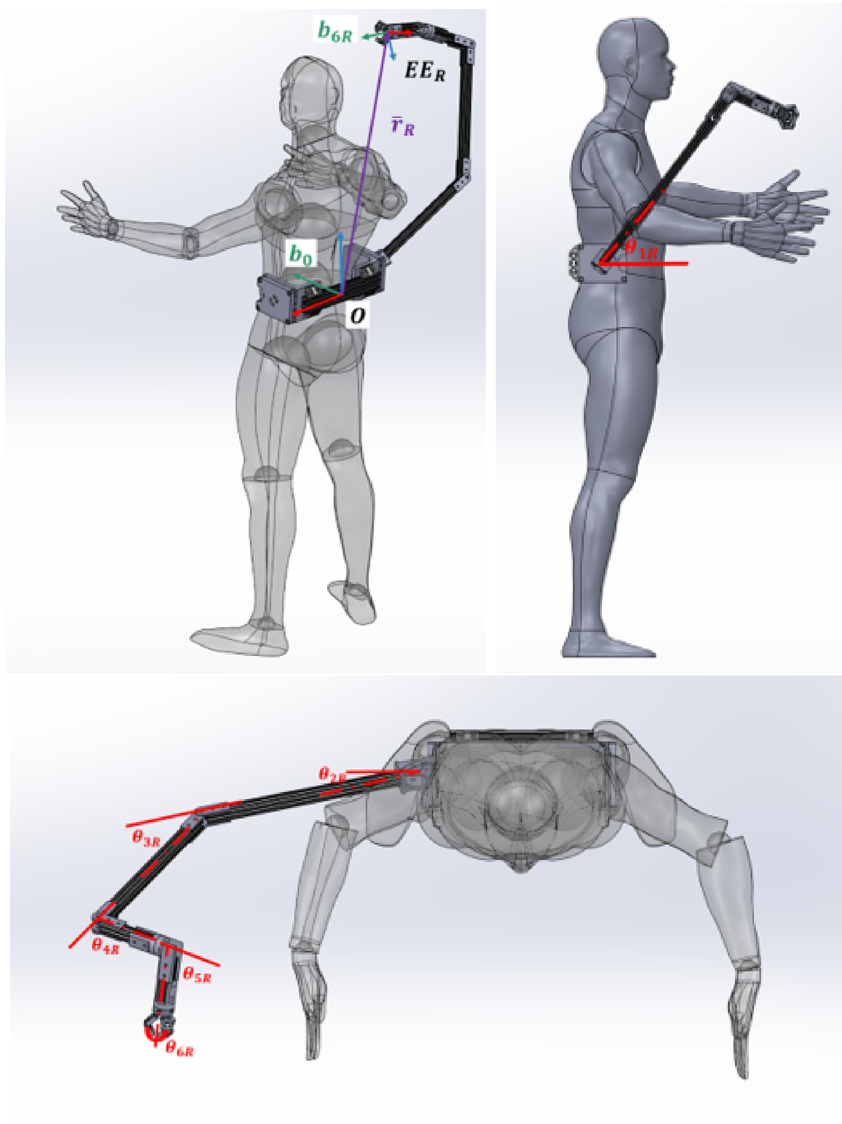


Figure 3-2: Generalized 3D Model of Space Suit SuperLimbs (Notation for right SuperLimb).

3.2 Generalized 3-D Model

For the 3-D model of the Space Suit SuperLimbs, each SuperLimb was modeled to directly reflect the geometry of a Universal Robots UR5e collaborative robotic platform. This in consequence requires analysis of two SuperLimbs each with six DoF.

To better understand the Space Suit SuperLimbs system, alike the 2-D model, lets define three key coordinate frames, the astronaut body frame $O_h - X_hY_hZ_h$, and the task space frames tied at the right $O_R - X_R Y_R Z_R$ and left $O_L - X_L Y_L Z_L$ end-effectors.

3.2.1 Forward Kinematics (FK) Derivation

Now lets define a set of 2 3x1 column vectors $\bar{r}_R$ and $\bar{r}_L$ that represents the displacement from the Astronaut body CoM to the end-effector tool center for the right and left SuperLimbs, respectively.

$$\bar{r}_R = \begin{Bmatrix} x_R & y_R & z_R \end{Bmatrix}^T, \bar{r}_L = \begin{Bmatrix} x_L & y_L & z_L \end{Bmatrix}^T \tag{3.7}$$

Knowing the orientation of each link on each SuperLimb, one can utilize the Euler angles method to map the human body frame to each end-effector frame.

$$\bar{r}_R = \bar{r}^0_{CoM} + \boldsymbol{R}_x(\theta_{1R})\bar{r}^1_0 + \boldsymbol{R}_x(\theta_{1R})\boldsymbol{R}_y(\theta_{2R})\bar{r}^2_1 + ... + \boldsymbol{R}_x(\theta_{1R})...\boldsymbol{R}_z(\theta_{6R})\bar{r}^6_5 \tag{3.8}$$

$$\bar{r}_L = \bar{r}^0_{CoM} + \boldsymbol{R}_x(\theta_{1L})\bar{r}^1_0 + \boldsymbol{R}_x(\theta_{1L})\boldsymbol{R}_y(\theta_{2L})\bar{r}^2_1 + ... + \boldsymbol{R}_x(\theta_{1L})...\boldsymbol{R}_z(\theta_{6L})\bar{r}^6_5 \tag{3.9}$$

The full rotation matrices required to map from the astronaut body frame to the task space frames can be expressed as

$$\boldsymbol{Q}_R = \boldsymbol{R}_x(\theta_{1R})\boldsymbol{R}_y(\theta_{2R})\boldsymbol{R}_y(\theta_{3R})\boldsymbol{R}_y(\theta_{4R})\boldsymbol{R}_x(\theta_{5R})\boldsymbol{R}_z(\theta_{6R}) \tag{3.10}$$

$$\boldsymbol{Q}_L = \boldsymbol{R}_x(\theta_{1L})\boldsymbol{R}_y(\theta_{2L})\boldsymbol{R}_y(\theta_{3L})\boldsymbol{R}_y(\theta_{4L})\boldsymbol{R}_x(\theta_{5L})\boldsymbol{R}_z(\theta_{6L}) \tag{3.11}$$

Provided this, both r_R/r_L and $\boldsymbol{Q}_R/\boldsymbol{Q}_L$ can be concatenated into homogeneous matrices to fully describe the forward kinematics of the end-effectors for the Space Suit SuperLimbs system.

$$\boldsymbol{T}_R = \begin{bmatrix} \boldsymbol{Q}_R & \bar{r}_R \\ \bar{0}^T & 1 \end{bmatrix}, \boldsymbol{T}_L = \begin{bmatrix} \boldsymbol{Q}_L & \bar{r}_L \\ \bar{0}^T & 1 \end{bmatrix} \tag{3.12}$$

Chapter 4

Statics

4.1 Solution using Jacobian

In order to determine the forces and torques necessary to statically brace the Astronaut's center of mass (CoM), one can simply utilize the Jacobian, J, found earlier.

Let $J^T \in R^6$ be the transpose of the Jacobian for the 2-D Space Suit SuperLimbs system and $J_C^T \in R^{2x6}$ be the transpose of the Jacobian due to constraints. Then, the forces and torques necessary to statically brace the Astronaut CoM can be expressed as

$$\boldsymbol{\tau} = -\boldsymbol{J_C^T} \begin{bmatrix} \tau_{3R} \\ \tau_{3L} \end{bmatrix} + \boldsymbol{J^T F} \tag{4.1}$$

where $\boldsymbol{F} \in R^6$ is the external load at the Astronaut CoM that can be interpreted as a load applied by the Astronaut.

4.2 Solution using Principle of Virtual Work

In order to assess the forces and torques acting on the Space Suit SuperLimbs system in 3-D, the *Principle of Virtual Work* [4] will be applied.

Let F_h and N_h be the forces and moments acting on the astronaut CoM, respectively. Also let F_R/F_L and N_R/N_L be the forces and moments acting on the right and

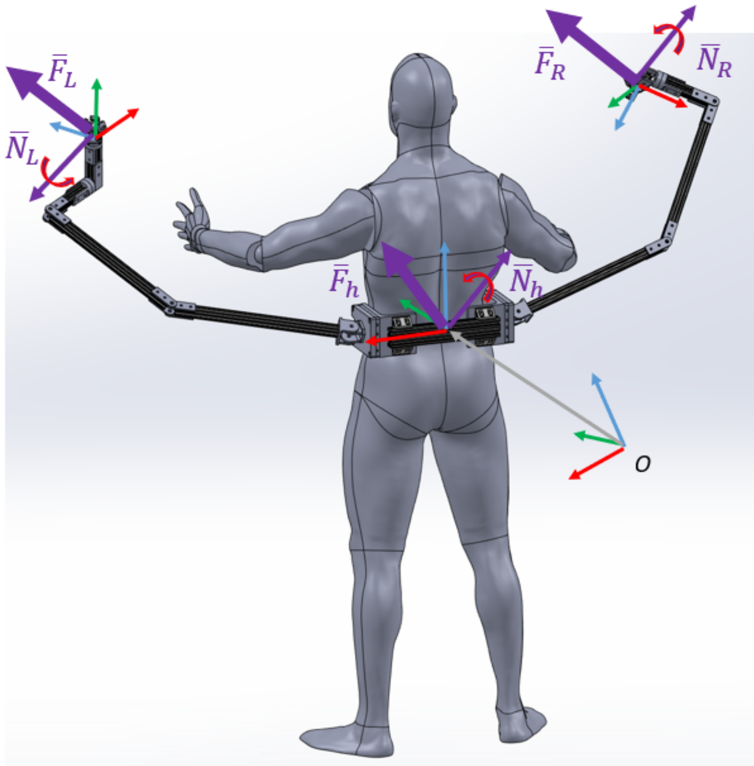


Figure 4-1: External Forces/Moments applied to Space Suit SuperLimbs System

left end-effectors, respectively. Finally, let τ_{Rj} and τ_{Li} represent the torques applied by joint j for the right SuperLimb and joint i for the left SuperLimb, respectively. Note: The effect of gravity is included in F_h and N_h.

The virtual work done by the entire system is

$$\delta_{work} = F_h^T \delta x_h + N_h^T \delta \phi_h + F_R^T \delta x_R + N_R^T \delta \phi_R + F_L^T \delta x_L + N_L^T \delta \phi_L + \sum_j \tau_{Rj} \delta q_{Rj} + \sum_l m_{Rl} g^T \cdot \delta x_{Rcl} + \sum_i \tau_{Li} \delta q_{Li} + \sum_k m_{Lk} g^T \cdot \delta x_{Lck} \quad (4.2)$$

where δx and $\delta \phi$ are virtual displacements.

The differential motion of each SuperLimb can be expressed as

$$\delta x_R = \delta x_h + \delta\phi_h \times P_R + J_{Rx}\delta q_R \tag{4.3}$$

$$\delta\phi_R = \delta\phi_h + J_{R\phi}\delta q_R \tag{4.4}$$

$$\delta x_L = \delta x_h + \delta\phi_h \times P_L + J_{Lx}\delta q_L \tag{4.5}$$

$$\delta\phi_L = \delta\phi_h + J_{L\phi}\delta q_L \tag{4.6}$$

where P_R and P_L represent the positions of the right and left end-effectors with respect to the astronaut body CoM, respectively. J_{Rx} and J_{Lx} are Jacobians that represent the linear component of the system's Jacobian, and $J_{R\phi}$ and $J_{L\phi}$ are Jacobians that represent the rotational component of the system's Jacobian for the right and left SuperLimb, respectively.

$$J_R = \begin{bmatrix} J_{Rx} \\ J_{R\phi} \end{bmatrix}, J_L = \begin{bmatrix} J_{Lx} \\ J_{L\phi} \end{bmatrix}$$

therefore

$$\begin{bmatrix} \delta x_R \\ \delta\phi_R \end{bmatrix} = J_R\delta q_R, \begin{bmatrix} \delta x_L \\ \delta\phi_L \end{bmatrix} = J_L\delta q_L$$

Note: $P^T = -P$.

Similarly, the virtual displacement of the center of mass ck of the kth link is

$$\delta x_{ck} = \delta x_h + \delta\phi_h \times P_{ck} + J_{xck}\delta q \tag{4.7}$$

Likewise, the virtual displacement of the center of mass cl of the lth link is

$$\delta x_{cl} = \delta x_h + \delta\phi_h \times P_{cl} + J_{xcl}\delta q \tag{4.8}$$

where J_{xck} and J_{xcl} are the Jacobians relating the linear differential displacement of ck and cl viewed from the astronaut body CoM, respectively.

By substituting 4.3, 4.7, and 4.8 into 4.2, the following is achieved:

$$
\begin{aligned}
\delta work = (F_h^T + F_R^T + F_L^T + (\sum_l m_{Rl} + \sum_k m_{Lk})g^T)\delta x_h \\
+ (N_h^T + F_R^T P_R + N_R^T + F_L^T P_L + N_L^T + (\sum_l m_{Rl} P_{Rcl} + \sum_k m_{Lk} P_{Rck})g^T)\delta\phi_k \\
+ (F_R^T J_{Rx} + N_R^T J_{R\phi} + \sum_l m_{Rl} g^T J_{Rxcl} + \tau_R^T)\delta q_R \\
+ (F_L^T J_{Lx} + N_L^T J_{L\phi} + \sum_k m_{Lk} g^T J_{Lxck} + \tau_L^T)\delta q_L \quad (4.9)
\end{aligned}
$$

By assessment of 4.9, in order for the virtual work to vanish for an arbitrary δx_h, $\delta\phi_h$, δq_R, and δq_L and therefore have a static system, the following conditions must be met:

$$
F_h^T + F_R^T + F_L^T + (\sum_l m_{Rl} + \sum_k m_{Lk})g^T = 0 \quad (4.10)
$$

$$
N_h^T + F_R^T P_R + N_R^T + F_L^T P_L + N_L^T + \sum_l m_{Rl} g^T P_{Rcl} + \sum_k m_{Lk} g^T P_{Rck} = 0 \quad (4.11)
$$

$$
F_R^T J_{Rx} + N_R^T J_{R\phi} + \sum_l m_{Rl} g^T J_{Rxcl} + \tau_R^T = 0 \quad (4.12)
$$

$$
F_L^T J_{Lx} + N_L^T J_{L\phi} + \sum_k m_{Lk} g^T J_{Lxck} + \tau_L^T = 0 \quad (4.13)
$$

Taking the transpose (Note: $P^T = -P$) yields

$$F_h + F_R + F_L + (\sum_l m_{Rl} + \sum_k m_{Lk})g = 0 \tag{4.14}$$

$$N_h - P_R F_R + N_R - P_L F_L + N_L - \sum_l m_{Rl} P_{Rcl} g - \sum_k m_{Lk} P_{Rck} g = 0 \tag{4.15}$$

$$J_{Rx}^T F_R + J_{R\phi}^T N_R + \sum_l m_{Rl} J_{Rxcl}^T g + \tau_R = 0 \tag{4.16}$$

$$J_{Lx}^T F_L + J_{L\phi}^T N_L + \sum_k m_{Lk} J_{Lxck}^T g + \tau_L = 0 \tag{4.17}$$

Under micro-gravity conditions, g can be approximated to 0, therefore

$$F_h + F_R + F_L = 0 \tag{4.18}$$

$$N_h - P_R F_R + N_R - P_L F_L + N_L = 0 \tag{4.19}$$

$$J_{Rx}^T F_R + J_{R\phi}^T N_R + \tau_R = 0 \tag{4.20}$$

$$J_{Lx}^T F_L + J_{L\phi}^T N_L + \tau_L = 0 \tag{4.21}$$

With this system of equations, the static bracing of the Space Suit SuperLimbs system can be easily modeled and validated against experimental data.

Chapter 5

Dynamics

5.1 Equations of Motion Derivation

In order to determine the equations of motion (EOM) for the Space Suit SuperLimbs system, the Lagrangian formulation was utilized. Before implementing this strategy, a few key assumptions must be made:

1. Gravity is in effect
2. Links are uniformly distributed masses; CoM for each link is at geometric center
3. Astronaut body mass is treated as a point mass

With this, the Lagrangian formulation can begin. Each joint within each SuperLimb can be utilized to express the generalized coordinates.

$$q_R = \begin{bmatrix} \theta_{1R} & \theta_{2R} & \ldots & \theta_{6R} \end{bmatrix}^T, q_L = \begin{bmatrix} \theta_{1L} & \theta_{2L} & \ldots & \theta_{6L} \end{bmatrix}^T$$

$$\dot{P} = \boldsymbol{J}\dot{q_R} = \boldsymbol{J}\dot{q_L} \rightarrow \dot{q_R} = \dot{q_L} = \boldsymbol{J^{-1}}\dot{P} \tag{5.1}$$

5.1 maps the task space to the joint space. However, for this analysis, the generalized coordinate vector must be expressed.

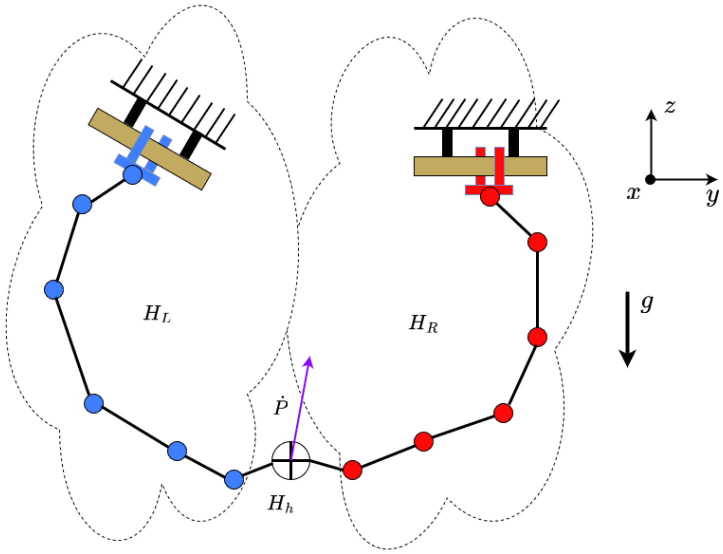


Figure 5-1: Simplified dynamic model of Space Suit SuperLimbs system

Let $\delta\boldsymbol{\phi}$ be a 6x1 generalized coordinate vector such that

$$\delta\phi_i = \sum_{k=1}^{i} \delta\theta_k \tag{5.2}$$

The kinetic energy of the Space Suit SuperLimbs system can be written as follows

$$\begin{aligned}\boldsymbol{T} = T_h + T_R + T_L &= \frac{1}{2}(\dot{P})^T H_h(\dot{P}) + \frac{1}{2}(\dot{P})^T H_R(\dot{P}) + \frac{1}{2}(\dot{P})^T H_L(\dot{P}) \\ &= \frac{1}{2}(\dot{P})^T[H_h + H_R + H_L](\dot{P}) = \frac{1}{2}(\dot{P})^T H(\dot{P})\end{aligned} \tag{5.3}$$

where in the joint space

$$\boldsymbol{T} = \frac{1}{2}(\dot{q})^T H_q(\dot{q})$$

and utilizing 5.1 results in

$$\boldsymbol{T} = \frac{1}{2}(\dot{P})^T(\boldsymbol{J^{-1}})^T H_q(\boldsymbol{J^{-1}})(\dot{P}) \tag{5.4}$$

therefore

$$H = (\boldsymbol{J^{-1}})^T H_q(\boldsymbol{J^{-1}}) \rightarrow H_R = (\boldsymbol{J_R^{-1}})^T H_{qR}(\boldsymbol{J_R^{-1}}), H_L = (\boldsymbol{J_L^{-1}})^T H_{qL}(\boldsymbol{J_L^{-1}})$$

Where $H_h \in R^6$, $H_R \in R^6$, and $H_L \in R^6$ represent the inertia tensors in the task space for the astronaut body CoM, right, and left SuperLimbs, respectively; and $H_{qR} \in R^6$ and $H_{qL} \in R^6$ represent the inertia tensors in the joint space for the right and left SuperLimbs, respectively.

Now kinetic energy must be expressed with respect to the generalized coordinates expressed in 5.2. This can be done by mapping the joint space expression for the kinetic energy shown in 5.4 to the generalized space

$$G = (\boldsymbol{J_\phi}^{-1})^T H_q(\boldsymbol{J_\phi}^{-1}) \tag{5.5}$$

where $G \in R^6$ is the generalized inertia tensor and $\boldsymbol{J_\phi}$ is the Jacobian that maps the generalized space to the task space. The diagonal elements of G represent the principle axes of the Generalized Inertia Ellipsoid (GIE).

With 5.5, the kinetic energy of the Space Suit SuperLimbs system can finally be expressed with respect to the generalized coordinates

$$\boldsymbol{T} = \frac{1}{2}(\dot{P})^T(\boldsymbol{J^{-1}})^T[(\boldsymbol{J_\phi^{-1}})G(\boldsymbol{J_\phi^{-1}})^T](\boldsymbol{J^{-1}})(\dot{P}) \tag{5.6}$$

Similarly, we can represent the potential energy of the Space Suit SuperLimbs system as the following

$$\boldsymbol{U} = U_h + U_R + U_L = m_h g P_z + \bar{m}_R g \cdot \bar{P}_{Rz} + \bar{m}_L g \cdot \bar{P}_{Lz} \tag{5.7}$$

where $\bar{m}_R \in R^6$ and $\bar{m}_L \in R^6$ are column vectors representing the masses of each link CoM for the right and left SuperLimbs, respectively; and $\bar{P}_{Rz} \in R^6$ and $\bar{P}_{Lz} \in R^6$ are column vectors representing the z-component (height) of each link CoM for the right and left SuperLimbs, respectively.

Now, lets define the generalized forces for the Space Suit SuperLimbs system. For this system, the only non-conservative forces acting are induced by the astronaut. For the sake of simplicity, lets assume the forces applied by the astronaut act directly on the astronaut body CoM. Therefore, the generalized forces can be approximated as

$$\boldsymbol{Q} = \boldsymbol{J_\phi} \boldsymbol{J^{-1}} \begin{bmatrix} \bar{\boldsymbol{F}}_{\boldsymbol{h}} \\ \bar{\boldsymbol{N}}_{\boldsymbol{h}} \end{bmatrix} \tag{5.8}$$

where $\boldsymbol{J_\phi} \boldsymbol{J^{-1}}$ is the sensitivity of the external forces to the generalized coordinates.

Finally, the EOM of the Space Suit SuperLimbs system can be expressed by the following

$$\frac{d}{dt}\left(\frac{\delta \boldsymbol{T}}{\delta \dot{P}}\right) - \frac{\delta \boldsymbol{T}}{\delta P} + \frac{\delta \boldsymbol{U}}{\delta P} = \boldsymbol{Q} \tag{5.9}$$

5.2 Inertia Analysis for Motor Torque Requirement

One key aspect to the design of the Space Suit SuperLimbs system is to be able to understand the minimum torque that each motor within the SuperLimbs is required to bear. To begin this analysis, lets maintain the same assumptions made in the EOM derivation, however, lets also make two additional assumptions:

- Motors are point masses centered at joints
- Position vector of astronaut CoM from right and left end-effectors are known

Lets start by defining the position vectors for each joint/link on the SuperLimbs recursively.

$$\underline{\mathrm{r}}_{ij} = \sum_{k=j+1}^{i} l_k \hat{e}_k \quad (i > j) \quad i = 1, 2, ..., 6 \tag{5.10}$$

$$\underline{\mathrm{r}}_{il_j} = \frac{l_j}{2}\hat{e}_j + \sum_{k=j+1}^{i} l_k \hat{e}_k \quad (i > j) \quad i = 1, 2, ..., 6 \tag{5.11}$$

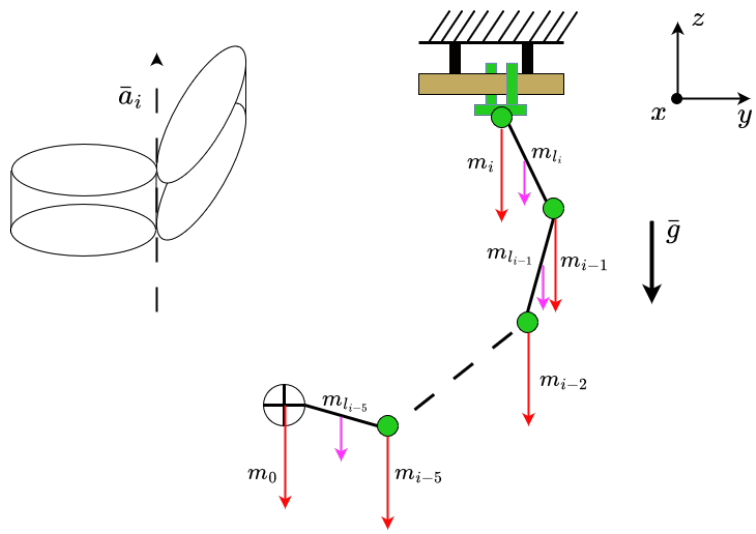


Figure 5-2: Representation of joints and links CoM

where $\underline{\mathrm{r}}_{ij}$ represents the position vector from joint i to joint j and $\underline{\mathrm{r}}_{il_j}$ represents the position vector from joint i to link CoM l_j.

Provided these position vectors, lets define the moment due to gravity for each joint.

$$\tau_{gi} = \underline{\mathrm{a}}_i \circ \sum_{j=0}^{i-1} [(\underline{\mathrm{r}}_{ij} \times \mathrm{g}) m_j + (\underline{\mathrm{r}}_{il_j} \times \mathrm{g}) m_{l_j}] \tag{5.12}$$

Additionally, the moment of inertia of the armature reflected upon joint i can be determined.

$$H_{qi} = I_{joints} + I_{links} = \sum_{j=0}^{i-1} [m_j |\underline{\mathrm{r}}_{ij} \times \underline{\mathrm{a}}_i|^2] + \sum_{j=1}^{i} [m_{l_j} |\underline{\mathrm{r}}_{il_j} \times \underline{\mathrm{a}}_i|^2] \tag{5.13}$$

Combining both 5.12 and 5.13, the minimum torque required by each motor on the SuperLimbs can be approximated by

$$\tau_{m_i} = \max_{\theta_1,\ldots,\theta_6} [\tau_{gi} + H_{qi} \alpha_i] \tag{5.14}$$

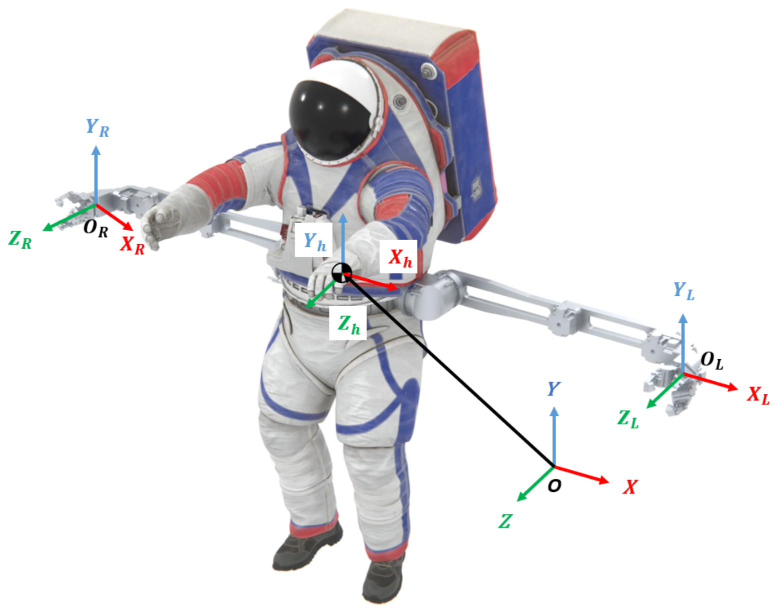


Figure 6-1: Space Suit SuperLimbs System Coordinate Frames.

Chapter 6

Control

6.1 Modeling

Coordinate systems are defined in Fig. $6-1$. Frame $O-XYZ$ is the Inertial Reference Frame, $O_R-X_RY_RZ_R$ and $O_L-X_LY_LZ_L$ are frames attached to the end-effectors of the right and left SuperLimbs, respectively. Let $\dot{P}_h \in R^6$ be velocity and angular velocity at the Center of Mass (CoM) of the human, while $\dot{P}_R, \dot{P}_L \in R^6$ be, respectively, those of the right and left end-effectors. We have

$$\dot{P}_R = J_R \dot{q}_R + \dot{P}_h \tag{6.1}$$

$$\dot{P}_L = J_L \dot{q}_L + \dot{P}_h \tag{6.2}$$

where $\dot{q}_R$, $\dot{q}_L \in \ R^6$ are joint velocities and J_R, $J_L \in \ R^{6x6}$ are the Jacobians of the right and left SuperLimbs, respectively. Suppose that the SuperLimbs are securely holding handrails on some structure of a spacecraft, $\dot{P}_R = \dot{P}_L = 0$. Then,

$$\therefore \dot{P}_h = -J_R \dot{q}_R = -J_L \dot{q}_L \tag{6.3}$$

Assuming that the entire astronaut's body, including the space suit and the Personal Protective Equipment (PPE), as a single body of total mass m_h and moment of inertia I_h, we obtain the equation of motion given by

$$\begin{aligned} m_h \ddot{X}_h &= \bar{\mathbf{F}}_\mathbf{h} \\ I_h \dot{\omega}_h + \omega_h \times (I \omega_h) &= \bar{\mathbf{N}}_\mathbf{h} \end{aligned} \tag{6.4}$$

where $\bar{\mathbf{F}}_\mathbf{h}$ and $\bar{\mathbf{N}}_\mathbf{h}$ are force and moment, or collectively a wrench, acting at the human CoM. Vectors $\dot{X}_h$ and ω_h are linear and angular velocities of $\dot{P}_h$, called a twist.

$$\mathbf{F}_h = \begin{bmatrix} \bar{\mathbf{F}}_\mathbf{h} \\ \bar{\mathbf{N}}_\mathbf{h} \end{bmatrix}, \dot{P}_h = \begin{bmatrix} \dot{X}_h \\ \omega_h \end{bmatrix} \tag{6.5}$$

It can be assumed that ω_h is small enough to ignore $\omega_h \times (I_h \omega_h)$, the above equation of motion can be reduced to

$$M \ddot{P}_h = \mathbf{F}_\mathbf{h} \tag{6.6}$$

$$\text{where } M = \begin{bmatrix} m_h I_3 & 0 \\ 0 & I_h \end{bmatrix} \tag{6.7}$$

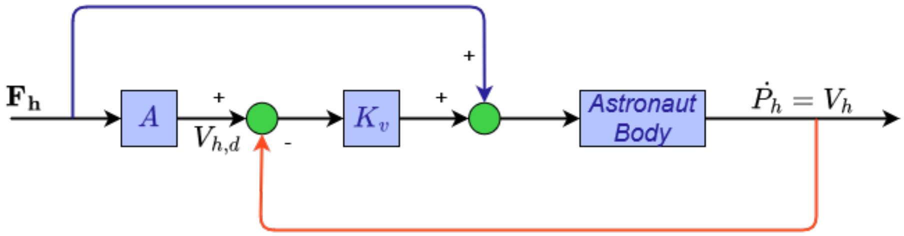


Figure 6-2: Admittance Control Synthesis Block Diagram for Space Suit SuperLimbs System.

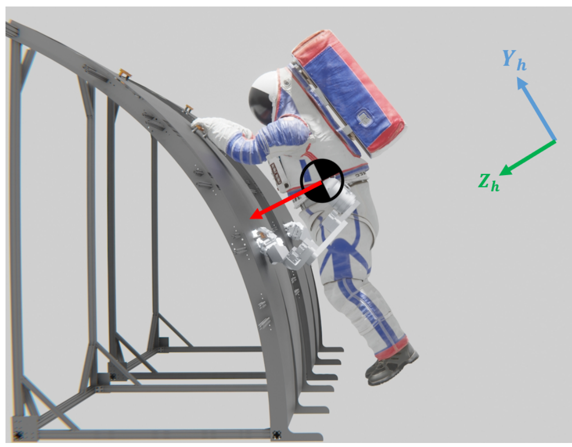


Figure 6-3: Proximity of astronaut to ISS external structure.

6.2 Admittance Control

Now we must define a control scheme that can allow the SuperLimbs to cooperatively work with the human operator [15], [22].

An astronaut must be able to change his/her position when performing EVA operations. Despite the significant inertia of the entire body M, the astronaut pushes/pulls the whole body by grabbing handrails on the exterior of the ISS for re-positioning the body. The SuperLimbs can assist the astronaut by virtually reducing the body inertia. Also, the SuperLimbs can brace the body to maintain the current position and orientation of the body. Furthermore, the SuperLimbs can bear a disturbing load acting on the body. Performing drilling work, for example, the astronaut must brace his/her body to absorb the disturbances generated by the hand-drill. Here, we consider the two functions of the SuperLimbs.

1. Virtually reduce the body inertia for agile and power-effective maneuvering.

2. Disturbance rejection by bracing the body.

Both functions required for the Space Suit SuperLimbs can be realized by controlling a functional relation between the wrench acting on the astronaut $\mathbf{F_h}$ and the resultant velocity of the body.

Consider the following admittance control law.

$$V_{h,d} = A\mathbf{F_h} \tag{6.8}$$

where $A \in \; R^{6x6}$ is an admittance matrix relating the body velocity to the wrench acting on the body that can be represented as a 2x2 matrix of 4 3x3 matrices, in the form.

$$A = \begin{bmatrix} A_{\dot{\bar{X}}\bar{f}} & A_{\dot{\bar{X}}\bar{N}} \\ A_{\dot{\phi}\bar{f}} & A_{\dot{\bar{\phi}}\bar{N}} \end{bmatrix} \tag{6.9}$$

Given these considerations, the elements of A are defined as follows

$$A_{\dot{\bar{X}}\bar{f}} = \begin{bmatrix} A_{X_X} & 0 & 0 \\ 0 & A_{Y_Y} & 0 \\ 0 & 0 & * \end{bmatrix} \tag{6.10}$$

$$A_{\dot{\bar{X}}\bar{N}} = \begin{bmatrix} 0 & -A_{X_\beta} & 2A_{X_\gamma} \\ A_{Y_\alpha} & 0 & -A_{Y_\gamma} \\ -2A_{Z_\alpha} & A_{Z_\beta} & 0 \end{bmatrix} \tag{6.11}$$

$$A_{\dot{\phi}\bar{f}} = \begin{bmatrix} 0 & -A_{\alpha_Y} & A_{\alpha_Z} \\ A_{\beta_X} & 0 & -A_{\beta_Z} \\ -A_{\gamma_X} & A_{\gamma_Y} & 0 \end{bmatrix} \tag{6.12}$$

$$A_{\dot{\bar{\phi}}\bar{N}} = \begin{bmatrix} A_{\alpha_\alpha} & 0 & 0 \\ 0 & A_{\beta_\beta} & 0 \\ 0 & 0 & A_{\gamma_\gamma} \end{bmatrix} \tag{6.13}$$

Where $*$ is an arbitrarily small scalar value.

The values for the non-zero elements of $A_{\bar{\dot{X}}\bar{N}}$ and $A_{\dot{\phi}\bar{f}}$ were selected to be arbitrarily small in order to maintain 1-to-1 6-DoF control.

Fig. $6-2$ shows the block diagram of the admittance control system. A velocity feedback control loop is formed from the actual astronaut's body velocity and angular velocity $\dot{P}_h$ with a velocity feedback gain matrix $K_v \in R^{6x6}$. The wrench $\mathbf{F_h}$ directly acts on the astronaut's body through the feedforward path at the top of the block diagram. The resultant wrench $\mathbf{F_h} + K_v(\dot{P}_{h,d} - \dot{P}_h)$ acts on the astronaut's body. The admittance control system measures the wrench $\mathbf{F_h}$ and computes the desired velocity $\dot{P}_{h,d}$ in response to $\mathbf{F_h}$, as stipulated by the admittance control law (6.8). The wrench $\mathbf{F_h}$ includes the force generated by the astronaut; when re-positioning, the astronaut pushes/pulls handrails, for example. The wrench $\mathbf{F_h}$ also includes a disturbance force generated during an EVA operation.

From the diagram and the equation of motion (6.6), we obtain

$$M\ddot{P}_h = \mathbf{F_h} + K_v(A\mathbf{F_h} - \dot{P}_h) \tag{6.14}$$

Taking the Laplace transform, we obtain

$$V_h = [K_v^{-1}Ms + I]^{-1}[A + K_v^{-1}]\mathbf{F_h} \tag{6.15}$$

where $V_h = \dot{P}_h$ and K_v is assumed non-singular. As the velocity gain matrix is sufficiently high, the above relationship reduces to

$$V_h \cong A\mathbf{F_h} \tag{6.16}$$

which is approximately the same as (6.8). For a finite K_v, note that the inertia felt by the astronaut virtually reduces to $K_v^{-1}M$ in (6.15). This is to meet the first functional requirement described above.

The admittance matrix A in (6.8) and (6.16) represents the inverse of a damping matrix. With a larger A, the damping virtually reduces, and the response becomes more agile. The two gain matrices, K_v and A, allow us to tune the behavior of the Space Suit SuperLimbs to desired dynamics.

As for the second functional requirement, the disturbance acting on the astronaut, $\mathbf{F_h}$, can be attenuated by assigning the admittance matrix A to

$$A = -\eta K_v^{-1} \tag{6.17}$$

where η is a parameter, $0 \leq \eta \leq 1$. Substituting this into (6.15) yields

$$V_h = [K_v^{-1} M s + I]^{-1}(1-\eta)\mathbf{F_h} \tag{6.18}$$

Setting $\eta = 1$ completely rejects the disturbances. This admittance control entails the measurement of the wrench $\mathbf{F_h}$ acting on the astronaut. As described previously, both SuperLimbs are equipped with 6 axis wrist force sensors measuring the wrench acting on the individual end-effectors. The wrench $\mathbf{F_h}$ can be estimated based on the two wrist force sensor measurements and the state of the astronaut motion. A Kalman Filter, for example, can be used for estimating $\hat{\mathbf{F_h}}$. In the current work, however, a simple method is used for estimating $\hat{\mathbf{F_h}}$ by assuming that $M\ddot{P}_h$ is small.

$$\hat{\mathbf{F_h}} = -S_R \mathbf{F_R^R} - S_L \mathbf{F_L^L} \tag{6.19}$$

where $\mathbf{F_R^R}$ and $\mathbf{F_L^L}$ are 6-axis force sensor readings at the right and left end-effectors in their coordinate frames, respectively, and S_R and S_L are transformation matrices between the end-effector frames and the human frame given by

$$S_i = \begin{bmatrix} I & 0 \\ s_i & I \end{bmatrix} \qquad s_i = \begin{bmatrix} 0 & -r_{zi} & r_{yi} \\ r_{zi} & 0 & -r_{xi} \\ -r_{yi} & r_{xi} & 0 \end{bmatrix} \tag{6.20}$$

where (r_x, r_y, r_z) are coordinates of each end-effector viewed from the human frame.

Chapter 7

Design and Implementation

In order to simulate the micro-gravity environment about the ISS, a full-scale mock-up would need to be constructed. A generalized 3 m (length) section of the exterior surface of the ISS was constructed from an array of extruded aluminum bars fitted to a custom water-jetted aluminum rib profile as shown in Fig. $7-1$. The mockup sections were then covered with large white polypropylene sheets to visually recreate the surface of a generalized ISS segment body as shown in Fig. $7-2$.

EVA handrails were constructed in-house out of stock brass bars, with a cross-sectional profile compliant to NASA-STD-3001 [13]. Each handrail was mounted to the ISS sectional mock-up with a load cell array at the base of each connection point, to act as a redundant set of measurements for F/T as shown in Fig. $7-3$. Each load cell array was connected to an Arduino Mega 2560 microcontroller for data recording.

We utilized two Universal Robots UR5e robots, which were connected to an extruded aluminum frame with a human mannequin rigidly installed, as shown in Fig. $7-4$. This entire prototype is suspended overhead by an enclosed rail capable of translating +/- 0.5 m in the X inertial axis to simulate a partial micro-gravity environment (along the X and Z inertial axes with consideration provided to restoring equilibrium forces due to gravity). To simulate the external structure, a full-scale sectional mock-up of the exterior of the ISS was developed, with the capability of

Figure 7-1: ISS exterior section mock-up (without panel coverings).

Figure 7-2: ISS EVA handrail mock-up with load cell array.

Figure 7-3: ISS exterior section mock-up (with panel coverings).

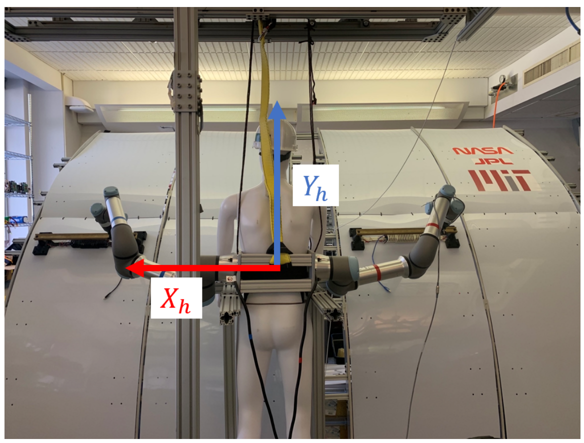


Figure 7-4: Space Suit SuperLimbs functional ground testing apparatus.

having instrumented EVA handrails installed at a variety of different locations.

The ACSS was developed in a Python script that communicates with two UR5e robots via ROS2 Foxy (and Real-Time Data Exchange (RTDE) as a redundancy). The UR5e's onboard F/T sensor data as well as the joint state data of each robot was acquired by directly subscribing to each telemetry topic and recording that data into a rosbag file at a stable sampling rate of 100 Hz, which was then converted into a .csv file for data synthesis.

Outside of the robot instrumentation, to measure the external loads applied by the test operator, a plate with an inline HX711 load cell will be pushed by the test operator and recorded separately at a stable sampling rate of 10 Hz.

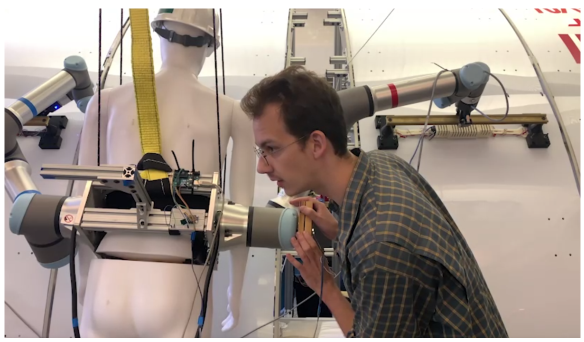


Figure 7-5: Push Test on Space Suit SuperLimbs prototype.

Chapter 8

Experimentation

8.1 Experimental Setup

In order to validate the Space Suit SuperLimbs system, two distinct experiments (and one simulation analysis) were performed on the prototype to validate both the physical implementation of the ACSS (with regard to its effectiveness in attenuating the effective inertial mass of the astronaut) as well as the Space Suit SuperLimbs' performance in statically bracing the astronaut.

1. To evaluate the attenuation in effective inertial mass, a low applied force (approximately 10 N) was applied in the $+/-X_h$ directions for each proportional gain setting, K_v, shown in Table 8.1 (with *Free Floating* referring to no SuperLimb connection with the structure, test operator is purely pushing the mass of the prototype). With each test the power, work, and time required for the test operator to successfully traverse the mannequin's CoM 0.33 m was determined. In this experimental setup, we considered that the tasks the astronaut would need to perform can be represented along the X_h axis.

2. To assess the static bracing performance, a compliance controller [19] was implemented onto the prototype with varying virtual stiffness, K, at a constant

Table 8.1: Astronaut performance with Space Suit SuperLimbs

Gain K_v	Avg. P (W)	W_d (J)	$t_{0.33m}$ (s)
Free Floating	6.10	53.53	7.8
2	3.85	33.75	5.5
3	3.50	24.25	5.4
5	3.33	12.75	4.7
10	2.97	10.31	3.9
25	1.29	7.50	3.4

applied load of 89 N (20 lbf) in the +/-X_h, +/-Y_h, and +/-Z_h directions for approximately 3 seconds, shown in Fig. $7-5$. For each test, the total deflection of one of the robot's end-effector position was recorded.

For both of these experiments, additional testing would need to be performed in a higher fidelity environment for micro-gravity EVAs (such as NASA's Neutral Buoyancy Laboratory (NBL) or Active Response Gravity Offload System (ARGOS)) in order to reaffirm the design of this system in 6 DoF.
In addition to these two experiments, an analysis in MATLAB was performed to investigate the Space Suit SuperLimbs' capacity to provide the astronaut with positional adjustment over a worksite. To perform this analysis, the astronaut's CoM workspace due to the SuperLimbs must be determined. By assuming that the SuperLimbs' end-effectors are rigidly fixed to the external structure, we analyzed the work spaces of both SuperLimbs with respect to their end-effectors, and overlapped them to determine the workspace for an astronaut's CoM.

8.2 Results/Discussion

During the execution of Experiment 1, the motion of the prototype's CoM was highly oscillatory in behavior with occasional unstable motion profiles that led to safeguards being activated by the URs and prematurely terminating tests. This was due to the fact that the force feedback of the experimental setup is non-collocated with a low sampling rate of 100 Hz [21]. A forward action is to optimize the prototype's controller for higher stable sampling rates to broaden the system's stability and repeat those tests with smoother motion profiles. Despite these hardware limitations, reasonable applied load data from the test operator was still captured and able to be disseminated for this study.

Fig. $8-1$ shows the power applied by the test operator over the time it takes to translate the prototype CoM 0.33 m from both a Free Floating configuration where the SuperLimbs are not rigidly fixated to any structure, and an active SuperLimb configuration (both end-effectors fixed to the structure) with a velocity feedback gain, K_v, of 5. For each test, the work applied by the test operator was calculated by integrating each power curve, fully tabulated in Table 8.1.

Fig. $8-2$ plots the total deflection of the prototype's CoM with varying stiffness from the compliance controller. It should be noted that $K = Max$ refers to a completely stiff set of SuperLimbs.

Fig. $8-3$ illustrates the overlap of both SuperLimb work spaces when the astronaut's CoM is 0.66 m from the external structure. This shows that the astronaut's workspace can be characterized by an ellipse with a major axis of 1.6 m in the Y axis and a minor axis of 1.0 m in the X axis.

The ACSS presents good performance in regards to reducing the overall effective inertial mass. The work required for an astronaut to propel their body is reduced with the admittance control design. Likewise, the Space Suit SuperLimbs show good static bracing performance, where the astronaut's CoM deflections are reduced and can be tuned.

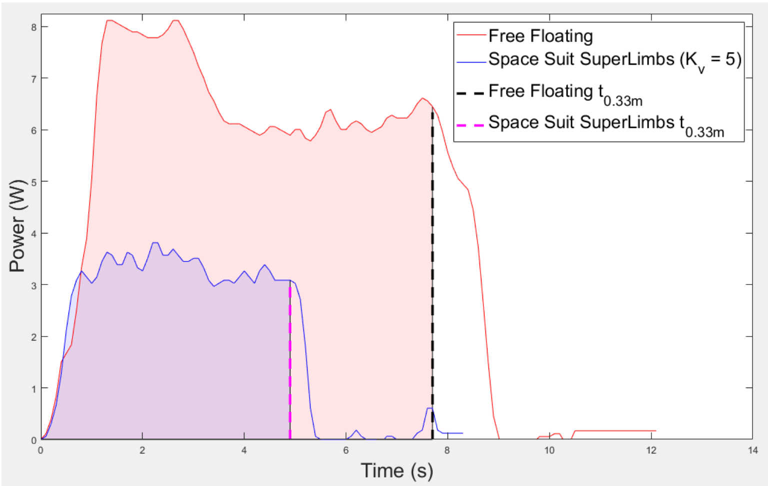


Figure 8-1: Power required by astronaut to translate 0.33 m.

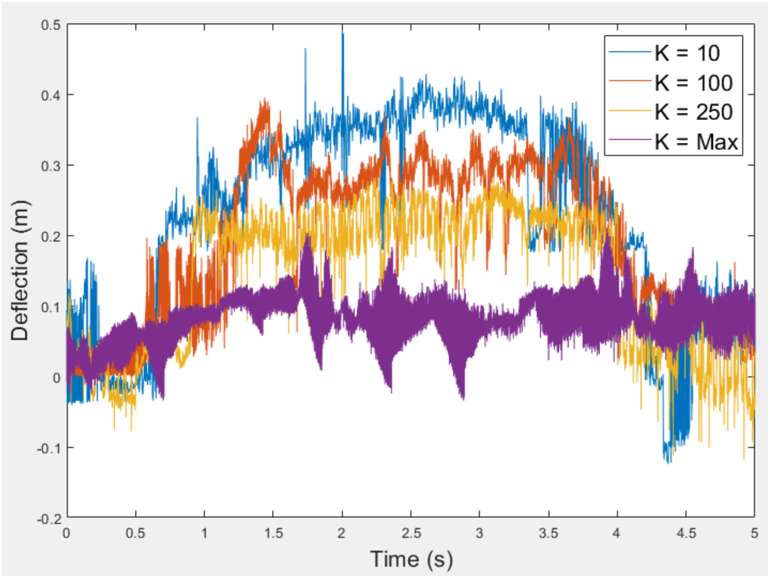


Figure 8-2: Total deflection of astronaut CoM during a stationary hold operation.

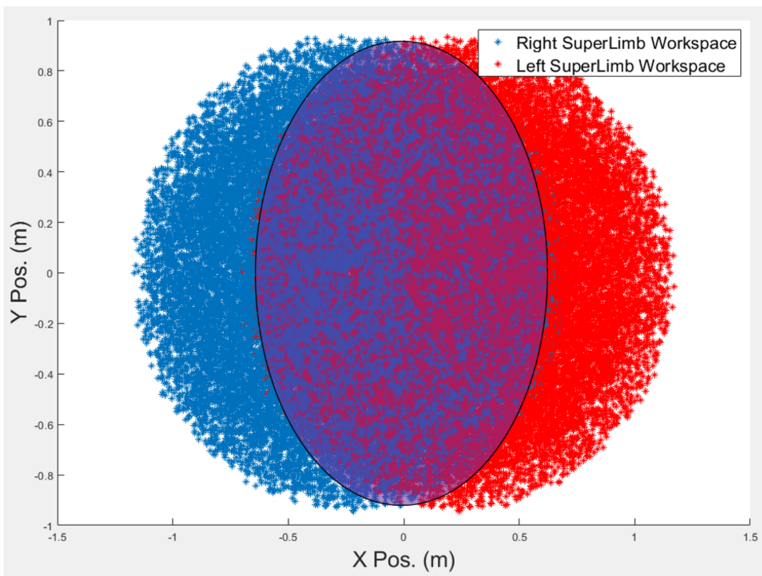


Figure 8-3: Rigid Tether allowable movement profile of astronaut CoM with astronaut CoM 0.66 m from external structure (shown in purple).

Chapter 9

Conclusion

In this study, we devised a novel integration approach to the way EVAs are conducted by attaching a pair of SuperLimbs to a space suit. For the initial development of this effort, we analyzed how the Space Suit SuperLimbs system affects micro-gravity EVAs and discovered that the system can provide risk mitigation for astronaut safety and health by alleviating conditions in which the astronaut must apply high joint torques within the space suit. This is done so by attenuating the effective overall inertial mass gained by the admittance control design as well as providing a portable and adjustable rigid tether through a means of disturbance rejection, allowing the astronaut more flexibility in worksite posturing as well as expanding the work envelope for astronauts. Simulation and experimental results show that this integration approach does in fact meet these analytical findings.

Future work will need to be conducted in regards to validating the disturbance rejection of the Space Suit SuperLimbs system. This can be done by conducting additional experiments that evaluates the Space Suit SuperLimbs' response to loads induced during common EVA worksite tasks, like the use of a hand-drill, and loads induced when an astronaut is actively transferring from one worksite to another.

The studies and development conducted thus far for the Space Suit SuperLimbs demonstrates a promising solution for future NASA EVAs. Future development of the Space Suit SuperLimbs system will be done so to align with NASA's current technological interests in planetary EVAs [1]. This means that the concepts discussed above will be expanded to worksite tasks with a partial gravity environment. This enables a much broader assortment of unique applications of SuperLimbs that will yield in the future further academic discussion.

Appendix A

Tables

Appendix B

Figures

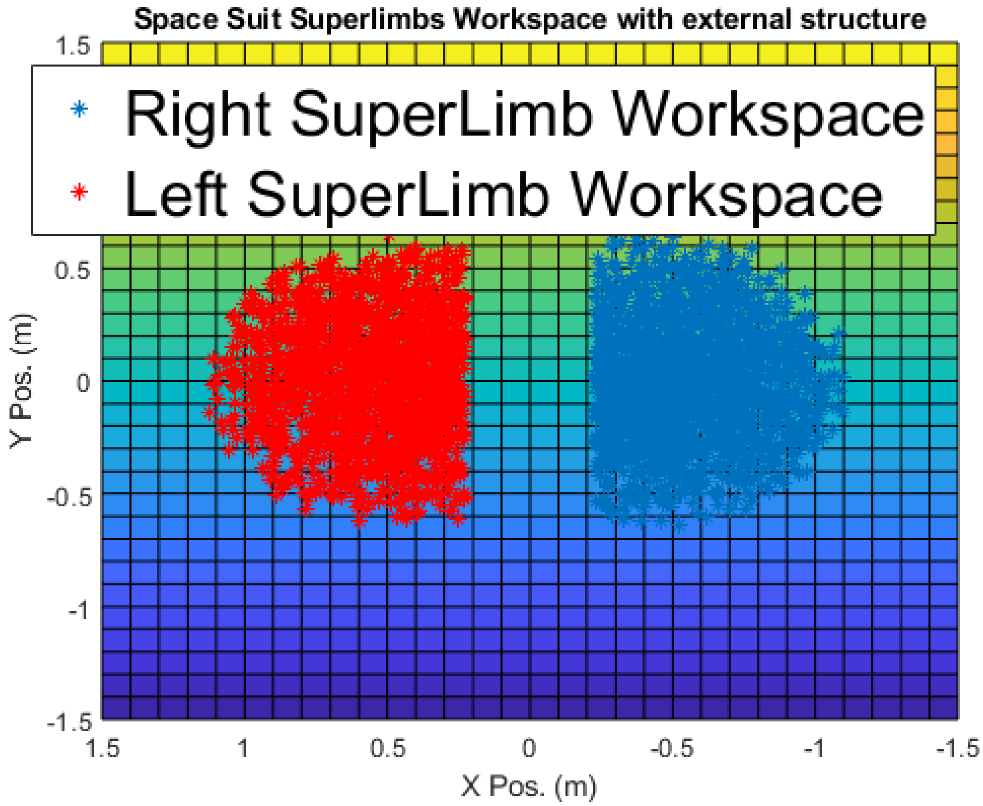
Contents

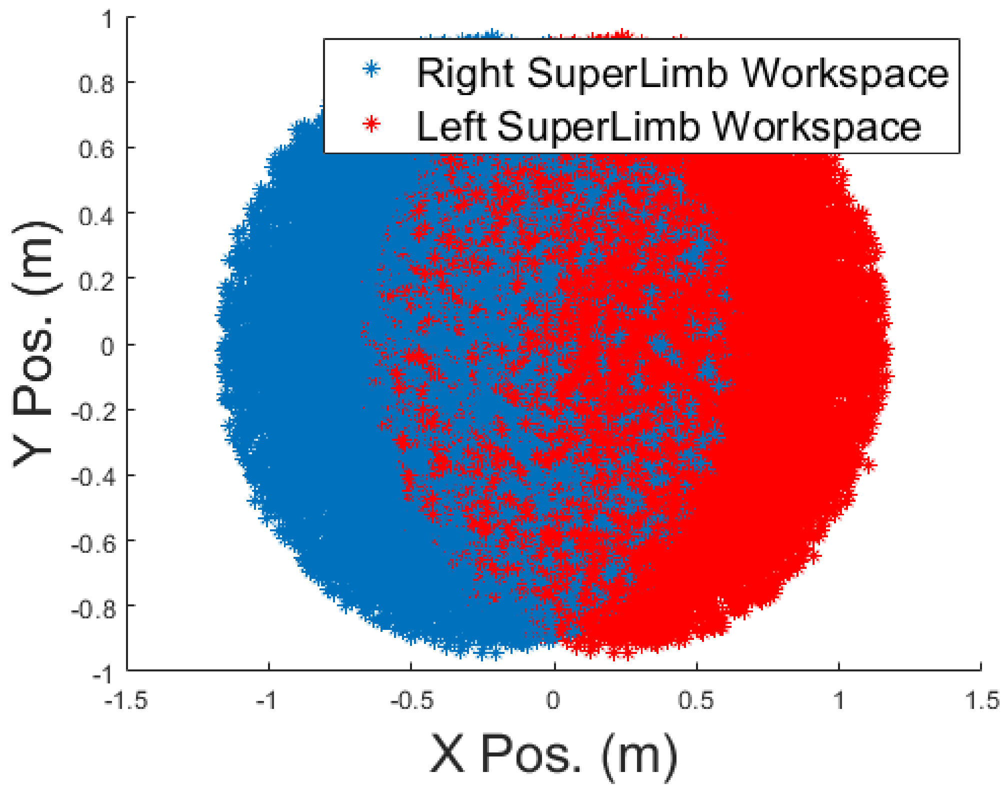

```
clc;
clear;
```

KINEMATIC MODEL OF MANTIS

```
for i = 1:100000
    q(i,:) = rand(6,1)*(2*pi);
end

theta_L = q;
theta_R = q;
alpha = [pi/2,0,0,pi/2,-pi/2,0]; %rad

%Linkage lengths (m)
l_UR5e = [152.4,89.2,425,392,109.3,94.75,82.5]/1000;
%Rotation matrices for each joint
for i = 1:length(theta_L)
    Rx1_L(:,:,i) = [1,0,0;0,cos(theta_L(i,1)),-sin(theta_L(i,1));0,sin(theta_L(i,1)),cos(theta_L(i,1))];
    Rz2_L(:,:,i) = [cos(theta_L(i,2)),-sin(theta_L(i,2)),0;sin(theta_L(i,2)),cos(theta_L(i,2)),0;0,0,1];
    Rz3_L(:,:,i) = [cos(theta_L(i,3)),-sin(theta_L(i,3)),0;sin(theta_L(i,3)),cos(theta_L(i,3)),0;0,0,1];
    Rz4_L(:,:,i) = [cos(theta_L(i,4)),-sin(theta_L(i,4)),0;sin(theta_L(i,4)),cos(theta_L(i,4)),0;0,0,1];
    Rx5_L(:,:,i) = [1,0,0;0,cos(theta_L(i,5)),-sin(theta_L(i,5));0,sin(theta_L(i,5)),cos(theta_L(i,5))];
    Rz6_L(:,:,i) = [cos(theta_L(i,6)),-sin(theta_L(i,6)),0;sin(theta_L(i,6)),cos(theta_L(i,6)),0;0,0,1];
    r_L(i,:) = [l_UR5e(1);0;0]+(Rx1_L(:,:,i)*[l_UR5e(2);0;0])+(Rx1_L(:,:,i)*Rz2_L(:,:,i)*[l_UR5e(3);0;0])+...
    (Rx1_L(:,:,i)*Rz2_L(:,:,i)*Rz3_L(:,:,i)*[l_UR5e(4);0;0])+...
    (Rx1_L(:,:,i)*Rz2_L(:,:,i)*Rz3_L(:,:,i)*Rz4_L(:,:,i)*[0;0;l_UR5e(5)])+...
    (Rx1_L(:,:,i)*Rz2_L(:,:,i)*Rz3_L(:,:,i)*Rz4_L(:,:,i)*Rx5_L(:,:,i)*[l_UR5e(6);0;0])+...
    (Rx1_L(:,:,i)*Rz2_L(:,:,i)*Rz3_L(:,:,i)*Rz4_L(:,:,i)*Rx5_L(:,:,i)*Rz6_L(:,:,i)*[0;0;l_UR5e(7)]);
    r_L(i,:) = r_L(i,:);
end
for i = 1:length(theta_R)
    Rx1_R(:,:,i) = [1,0,0;0,cos(theta_R(i,1)),-sin(theta_R(i,1));0,sin(theta_R(i,1)),cos(theta_R(i,1))];
    Rz2_R(:,:,i) = [cos(theta_R(i,2)),-sin(theta_R(i,2)),0;sin(theta_R(i,2)),cos(theta_R(i,2)),0;0,0,1];
    Rz3_R(:,:,i) = [cos(theta_R(i,3)),-sin(theta_R(i,3)),0;sin(theta_R(i,3)),cos(theta_R(i,3)),0;0,0,1];
    Rz4_R(:,:,i) = [cos(theta_R(i,4)),-sin(theta_R(i,4)),0;sin(theta_R(i,4)),cos(theta_R(i,4)),0;0,0,1];
    Rx5_R(:,:,i) = [1,0,0;0,cos(theta_R(i,5)),-sin(theta_R(i,5));0,sin(theta_R(i,5)),cos(theta_R(i,5))];
    Rz6_R(:,:,i) = [cos(theta_R(i,6)),-sin(theta_R(i,6)),0;sin(theta_R(i,6)),cos(theta_R(i,6)),0;0,0,1];
    r_R(i,:) = [l_UR5e(1);0;0]+(Rx1_R(:,:,i)*[l_UR5e(2);0;0])+...
    (Rx1_R(:,:,i)*Rz2_R(:,:,i)*[l_UR5e(3);0;0])+(Rx1_R(:,:,i)*Rz2_R(:,:,i)*Rz3_R(:,:,i)*[l_UR5e(4);0;0])+...
    (Rx1_R(:,:,i)*Rz2_R(:,:,i)*Rz3_R(:,:,i)*Rz4_R(:,:,i)*[0;0;l_UR5e(5)])+...
    (Rx1_R(:,:,i)*Rz2_R(:,:,i)*Rz3_R(:,:,i)*Rz4_R(:,:,i)*Rx5_R(:,:,i)*[l_UR5e(6);0;0])+...
    (Rx1_R(:,:,i)*Rz2_R(:,:,i)*Rz3_R(:,:,i)*Rz4_R(:,:,i)*Rx5_R(:,:,i)*Rz6_R(:,:,i)*[0;0;l_UR5e(7)]);
    r_R(i,:) = r_R(i,:);
end

Ry_pos_180 = [cos(pi),0,sin(pi);0,1,0;-sin(pi),0,cos(pi)];
Ry_pos_90 = [cos(pi/2),0,sin(pi/2);0,1,0;-sin(pi/2),0,cos(pi/2)];
Rz_pos_90 = [cos(pi/2),-sin(pi/2),0;sin(pi/2),cos(pi/2),0;0,0,1];

r_R_alt = r_R;
r_L_alt = r_L;

for i = 1:length(theta_R)
    if r_R(i,1) < 0
```

```
        r_R(i,:) = NaN;
    end
    r_R(i,:) = r_R(i,:) + [0.1524*1.5,0,0];
    r_R(i,:) = Ry_pos_180*transpose(r_R(i,:));
    if r_L(i,1) < 0
        r_L(i,:) = NaN;
    end
    r_L(i,:) = r_L(i,:) + [0.1524*1.5,0,0];
end

for i = 1:length(theta_R)
    if r_R_alt(i,1) < 0
        r_R_alt(i,:) = NaN;
    end
    r_R_alt(i,:) = r_R_alt(i,:) + [0,0.1524*1.5,0];
    r_R_alt(i,:) = Rz_pos_90*Ry_pos_90*transpose(r_R_alt(i,:));
    if r_L_alt(i,1) < 0
        r_L_alt(i,:) = NaN;
    end
    r_L_alt(i,:) = r_L_alt(i,:) + [0,-0.1524*1.5,0];
    r_L_alt(i,:) = Rz_pos_90*Ry_pos_90*transpose(r_L_alt(i,:));
end

%PLOT SURFACE REPRESENTING EXTERNAL SURFACE
d = 0.66; %m
[x z] = meshgrid(-1.5:0.1:1.5);
y = d*ones(size(x,1));
y2 = -d*ones(size(x,1));
for i = 1:length(r_R_alt)
    if r_R_alt(i,3) < -d
        r_R_alt(i,:) = NaN;
    end
    if r_L_alt(i,3) < -d
        r_L_alt(i,:) = NaN;
    end
end

figure(1);
plot3(r_R(:,1),r_R(:,3),r_R(:,2),'*');
hold on
plot3(r_L(:,1),r_L(:,3),r_L(:,2),'r*');
hold on
surf(x,y,z);
xlabel('X Pos. (m)');
ylabel('Z Pos. (m)');
zlabel('Y Pos. (m)')
view([180,0]);
legend('Right SuperLimb Workspace','Left SuperLimb Workspace','location','NorthEast','FontSize',24);
title('Space Suit Superlimbs Workspace with external structure');

figure(2);
plot3(r_R_alt(:,1),r_R_alt(:,3),r_R_alt(:,2),'*');
hold on
plot3(r_L_alt(:,1),r_L_alt(:,3),r_L_alt(:,2),'r*');
xlabel('X Pos. (m)','fontsize',20);
ylabel('Z Pos. (m)','fontsize',20);
zlabel('Y Pos. (m)','fontsize',20);
view([0,0]);
legend('Right SuperLimb Workspace','Left SuperLimb Workspace','location','NorthEast','fontsize',16);
%title('Rigid Tether allowable movement profile of Human CoM w/ Human CoM @ 2 ft from external structure');
```





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Contents

DATA PROCESSOR FOR COMPLIANCE CONTROL/DISTURBANCE REJECTION TESTING CAMPAIGN

```
clc;
clear;
```

X DIRECTION APPLIED OPERATOR FORCE %%

```
%%PROCESSING OF IMU AND OPERATION LOAD CELL DATA%%
K_max_IMU_LC_x = readmatrix("K_max_pose_2\IMU_LC_Data\test_x_1_1.csv");
K_250_IMU_LC_x = readmatrix("K_250_pose_4\IMU_LC_Data\test_x_3_1.csv");
K_10_IMU_LC_x = readmatrix("K_10_pose_3\IMU_LC_Data\test_x_2_1.csv");
K_transfer_IMU_LC_x = readmatrix("K_Transfer\IMU_LC_Data\Test_x.csv");
K_worksite_IMU_LC_x = readmatrix("K_Worksite\IMU_LC_Data\Test_x.csv");

K_max_IMU_x = [K_max_IMU_LC_x(:,3:6)];
K_250_IMU_x = [K_250_IMU_LC_x(:,3:6)];
K_10_IMU_x = [K_10_IMU_LC_x(:,3:6)];
K_transfer_IMU_x = [K_transfer_IMU_LC_x(:,3:6)];
K_worksite_IMU_x = [K_worksite_IMU_LC_x(:,3:6)];

K_max_LC_x = K_max_IMU_LC_x(:,2:3);
K_250_LC_x = K_250_IMU_LC_x(:,2:3);
K_10_LC_x = K_10_IMU_LC_x(:,2:3);
K_transfer_LC_x = K_transfer_IMU_LC_x(:,2:3);
K_worksite_LC_x = K_worksite_IMU_LC_x(:,2:3);

%%PLOT X OPERATOR LOAD CELL DATA%%
figure(1)
subplot(5,1,1)
plot(K_max_LC_x(:,1),K_max_LC_x(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=MAX)');
subplot(5,1,2)
plot(K_250_LC_x(:,1),K_250_LC_x(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=250)');
subplot(5,1,3)
plot(K_10_LC_x(:,1),K_10_LC_x(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=10)');
subplot(5,1,4)
```

```
plot(K_transfer_LC_x(:,1),K_transfer_LC_x(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=transfer)');
subplot(5,1,5)
plot(K_worksite_LC_x(:,1),K_worksite_LC_x(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=worksite)');

%%PLOT IMU DATA%%
figure(2)
subplot(5,1,1)
plot(K_max_IMU_x(:,1),K_max_IMU_x(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=MAX)');
subplot(5,1,2)
plot(K_250_IMU_x(:,1),K_250_IMU_x(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=250)');
subplot(5,1,3)
plot(K_10_IMU_x(:,1),K_10_IMU_x(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=10)');
subplot(5,1,4)
plot(K_transfer_IMU_x(:,1),K_transfer_IMU_x(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=transfer)');
subplot(5,1,5)
plot(K_worksite_IMU_x(:,1),K_worksite_IMU_x(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=worksite)');

%%PROCESSING OF HANDRAIL DATA%%
K_max_R_HR_x = readmatrix("K_max_pose_2\Handrail_Data\test_x_1_1_black.csv");
K_max_L_HR_x = readmatrix("K_max_pose_2\Handrail_Data\test_x_1_1_white.csv");
K_250_R_HR_x = readmatrix("K_250_pose_4\Handrail_Data\test_x_3_1_black.csv");
K_250_L_HR_x = readmatrix("K_250_pose_4\Handrail_Data\test_x_3_1_white.csv");
K_10_R_HR_x = readmatrix("K_10_pose_3\Handrail_Data\test_x_2_1_black.csv");
K_10_L_HR_x = readmatrix("K_10_pose_3\Handrail_Data\test_x_2_1_white.csv");
K_transfer_R_HR_x = readmatrix("K_Transfer\Handrail_Data\test_x_black.csv");
K_transfer_L_HR_x = readmatrix("K_Transfer\Handrail_Data\test_x_white.csv");
K_worksite_R_HR_x = readmatrix("K_Worksite\Handrail_Data\test_x_black.csv");
K_worksite_L_HR_x = readmatrix("K_Worksite\Handrail_Data\test_x_white.csv");

%%PLOT HANDRAIL DATA%%
figure(3)
subplot(5,2,1)
plot(K_max_L_HR_x(:,1),K_max_L_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=MAX)');
subplot(5,2,2)
plot(K_max_R_HR_x(:,1),K_max_R_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=MAX)');
subplot(5,2,3)
plot(K_250_L_HR_x(:,1),K_250_L_HR_x(:,2:5));
```

```
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=250)');
subplot(5,2,4)
plot(K_250_R_HR_x(:,1),K_250_R_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=250)');
subplot(5,2,5)
plot(K_10_L_HR_x(:,1),K_10_L_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=10)');
subplot(5,2,6)
plot(K_10_R_HR_x(:,1),K_10_R_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=10)');
subplot(5,2,7)
plot(K_transfer_L_HR_x(:,1),K_transfer_L_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_HR_x(:,1),K_transfer_R_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_HR_x(:,1),K_worksite_L_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_HR_x(:,1),K_worksite_R_HR_x(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=worksite)');

%%PROCESSING OF UR5E DATA%%
K_max_R_FT_x = readmatrix("K_max_pose_2\UR5e_Data\test_x_1_1\right_ft_data_adjusted.csv");
K_max_L_FT_x = readmatrix("K_max_pose_2\UR5e_Data\test_x_1_1\left_ft_data_adjusted.csv");
K_250_R_FT_x = readmatrix("K_250_pose_4\UR5e_Data\test_x_3_1\right_ft_data.csv");
K_250_L_FT_x = readmatrix("K_250_pose_4\UR5e_Data\test_x_3_1\left_ft_data.csv");
K_10_R_FT_x = readmatrix("K_10_pose_3\UR5e_Data\test_x_2_1\right_ft_data.csv");
K_10_L_FT_x = readmatrix("K_10_pose_3\UR5e_Data\test_x_2_1\left_ft_data.csv");
K_transfer_R_FT_x = readmatrix("K_Transfer\UR5e_Data\K_Transfer_X\right_ft_data.csv");
K_transfer_L_FT_x = readmatrix("K_Transfer\UR5e_Data\K_Transfer_X\left_ft_data.csv");
K_worksite_R_FT_x = readmatrix("K_Worksite\UR5e_Data\K_Worksite_X\right_ft_data.csv");
K_worksite_L_FT_x = readmatrix("K_Worksite\UR5e_Data\K_Worksite_X\left_ft_data.csv");

K_max_R_FT_x = [K_max_R_FT_x(:,3),K_max_R_FT_x(:,5:10)];
K_max_L_FT_x = [K_max_L_FT_x(:,3),K_max_L_FT_x(:,5:10)];
K_250_R_FT_x = [K_250_R_FT_x(:,3),K_250_R_FT_x(:,5:10)];
K_250_L_FT_x = [K_250_L_FT_x(:,3),K_250_L_FT_x(:,5:10)];
K_10_R_FT_x = [K_10_R_FT_x(:,3),K_10_R_FT_x(:,5:10)];
K_10_L_FT_x = [K_10_L_FT_x(:,3),K_10_L_FT_x(:,5:10)];
K_transfer_R_FT_x = [K_transfer_R_FT_x(:,3),K_transfer_R_FT_x(:,5:10)];
K_transfer_L_FT_x = [K_transfer_L_FT_x(:,3),K_transfer_L_FT_x(:,5:10)];
K_worksite_R_FT_x = [K_worksite_R_FT_x(:,3),K_worksite_R_FT_x(:,5:10)];
K_worksite_L_FT_x = [K_worksite_L_FT_x(:,3),K_worksite_L_FT_x(:,5:10)];
```

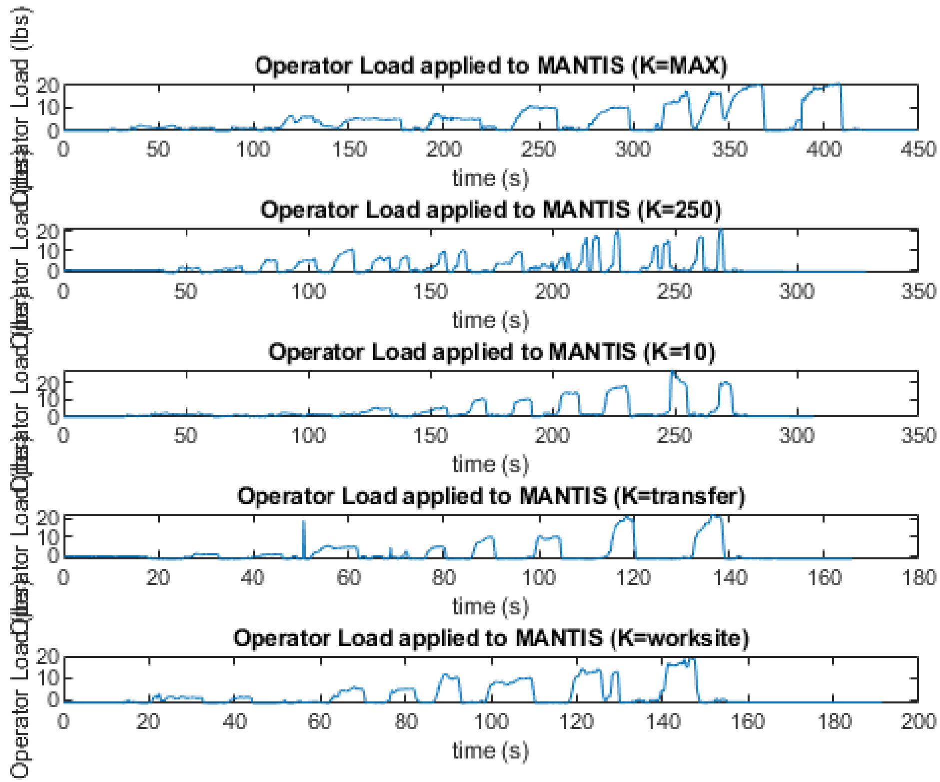
```
K_max_R_Jt_Trq_x = readmatrix("K_max_pose_2\UR5e_Data\test_x_1_1\right_joint_torques.csv");
K_max_L_Jt_Trq_x = readmatrix("K_max_pose_2\UR5e_Data\Test_x_1_1\left_joint_torques.csv");
K_250_R_Jt_Trq_x = readmatrix("K_250_pose_4\UR5e_Data\test_x_3_1\right_joint_torques.csv");
K_250_L_Jt_Trq_x = readmatrix("K_250_pose_4\UR5e_Data\test_x_3_1\left_joint_torques.csv");
K_10_R_Jt_Trq_x = readmatrix("K_10_pose_3\UR5e_Data\test_x_2_1\right_joint_torques.csv");
K_10_L_Jt_Trq_x = readmatrix("K_10_pose_3\UR5e_Data\test_x_2_1\left_joint_torques.csv");
K_transfer_R_Jt_Trq_x = readmatrix("K_Transfer\UR5e_Data\K_Transfer_X\right_joint_torques.csv");
K_transfer_L_Jt_Trq_x = readmatrix("K_Transfer\UR5e_Data\K_Transfer_X\left_joint_torques.csv");
K_worksite_R_Jt_Trq_x = readmatrix("K_Worksite\UR5e_Data\K_Worksite_X\right_joint_torques.csv");
K_worksite_L_Jt_Trq_x = readmatrix("K_Worksite\UR5e_Data\K_Worksite_X\left_joint_torques.csv");

K_max_R_Jt_Trq_x = K_max_R_Jt_Trq_x(:,2:8);
K_max_L_Jt_Trq_x = K_max_L_Jt_Trq_x(:,2:8);
K_250_R_Jt_Trq_x = K_250_R_Jt_Trq_x(:,2:8);
K_250_L_Jt_Trq_x = K_250_L_Jt_Trq_x(:,2:8);
K_10_R_Jt_Trq_x = K_10_R_Jt_Trq_x(:,2:8);
K_10_L_Jt_Trq_x = K_10_L_Jt_Trq_x(:,2:8);
K_transfer_R_Jt_Trq_x = K_transfer_R_Jt_Trq_x(:,2:8);
K_transfer_L_Jt_Trq_x = K_transfer_L_Jt_Trq_x(:,2:8);
K_worksite_R_Jt_Trq_x = K_worksite_R_Jt_Trq_x(:,2:8);
K_worksite_L_Jt_Trq_x = K_worksite_L_Jt_Trq_x(:,2:8);

K_max_R_Jt_State_x = readmatrix("K_max_pose_2\UR5e_Data\test_x_1_1\right_joint_states.csv");
K_max_L_Jt_State_x = readmatrix("K_max_pose_2\UR5e_Data\test_x_1_1\left_joint_states.csv");
K_250_R_Jt_State_x = readmatrix("K_250_pose_4\UR5e_Data\test_x_3_1\right_joint_states.csv");
K_250_L_Jt_State_x = readmatrix("K_250_pose_4\UR5e_Data\test_x_3_1\left_joint_states.csv");
K_10_R_Jt_State_x = readmatrix("K_10_pose_3\UR5e_Data\test_x_2_1\right_joint_states.csv");
K_10_L_Jt_State_x = readmatrix("K_10_pose_3\UR5e_Data\test_x_2_1\left_joint_states.csv");
K_transfer_R_Jt_State_x = readmatrix("K_Transfer\UR5e_Data\K_Transfer_X\right_joint_states.csv");
K_transfer_L_Jt_State_x = readmatrix("K_Transfer\UR5e_Data\K_Transfer_X\left_joint_states.csv");
K_worksite_R_Jt_State_x = readmatrix("K_Worksite\UR5e_Data\K_Worksite_X\right_joint_states.csv");
K_worksite_L_Jt_State_x = readmatrix("K_Worksite\UR5e_Data\K_Worksite_X\left_joint_states.csv");

K_max_R_Jt_State_x = [K_max_R_Jt_State_x(:,3),K_max_R_Jt_State_x(:,10:15)];
K_max_L_Jt_State_x = [K_max_L_Jt_State_x(:,3),K_max_L_Jt_State_x(:,10:15)];
K_250_R_Jt_State_x = [K_250_R_Jt_State_x(:,3),K_250_R_Jt_State_x(:,10:15)];
K_250_L_Jt_State_x = [K_250_L_Jt_State_x(:,3),K_250_L_Jt_State_x(:,10:15)];
K_10_R_Jt_State_x = [K_10_R_Jt_State_x(:,3),K_10_R_Jt_State_x(:,10:15)];
K_10_L_Jt_State_x = [K_10_L_Jt_State_x(:,3),K_10_L_Jt_State_x(:,10:15)];
K_transfer_R_Jt_State_x = [K_transfer_R_Jt_State_x(:,3),K_transfer_R_Jt_State_x(:,10:15)];
K_transfer_L_Jt_State_x = [K_transfer_L_Jt_State_x(:,3),K_transfer_L_Jt_State_x(:,10:15)];
K_worksite_R_Jt_State_x = [K_worksite_R_Jt_State_x(:,3),K_worksite_R_Jt_State_x(:,10:15)];
K_worksite_L_Jt_State_x = [K_worksite_L_Jt_State_x(:,3),K_worksite_L_Jt_State_x(:,10:15)];

%%PLOT UR5E DATA%%
figure(4)
subplot(5,2,1)
plot(K_max_L_FT_x(:,1),K_max_L_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=MAX)');
subplot(5,2,2)
plot(K_max_R_FT_x(:,1),K_max_R_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=MAX)');
subplot(5,2,3)
plot(K_250_L_FT_x(:,1),K_250_L_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
```

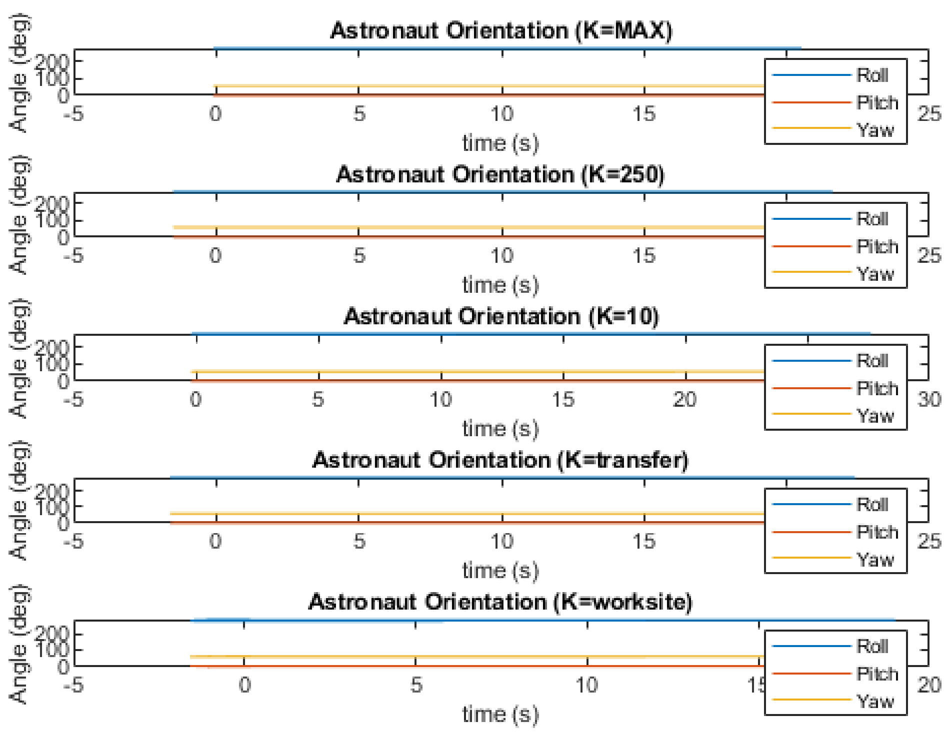
```
plot(K_250_R_FT_x(:,1),K_250_R_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_x(:,1),K_10_L_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_x(:,1),K_10_R_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_x(:,1),K_transfer_L_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_FT_x(:,1),K_transfer_R_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_FT_x(:,1),K_worksite_L_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_x(:,1),K_worksite_R_FT_x(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (N)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=worksite)');

figure(5)
subplot(5,2,1)
plot(K_max_L_FT_x(:,1),K_max_L_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=MAX)');
subplot(5,2,2)
plot(K_max_R_FT_x(:,1),K_max_R_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=MAX)');
subplot(5,2,3)
plot(K_250_L_FT_x(:,1),K_250_L_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_x(:,1),K_250_R_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_x(:,1),K_10_L_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
```

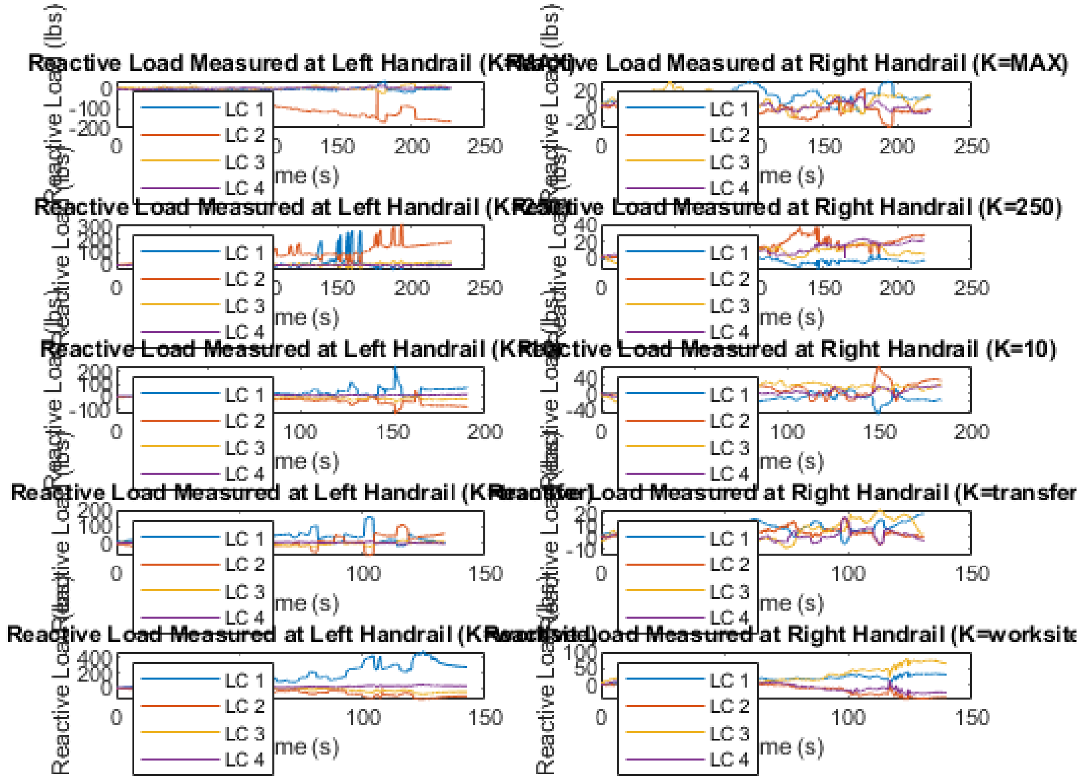
```
plot(K_10_R_FT_x(:,1),K_10_R_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_x(:,1),K_transfer_L_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_worksite_R_FT_x(:,1),K_worksite_R_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');
subplot(5,2,9)
plot(K_worksite_L_FT_x(:,1),K_worksite_L_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_x(:,1),K_worksite_R_FT_x(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');

figure(6)
subplot(5,2,1)
plot(K_max_L_Jt_Trq_x(:,1),K_max_L_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=MAX)');
subplot(5,2,2)
plot(K_max_R_Jt_Trq_x(:,1),K_max_R_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=MAX)');
subplot(5,2,3)
plot(K_250_L_Jt_Trq_x(:,1),K_250_L_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_Trq_x(:,1),K_250_R_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_Trq_x(:,1),K_10_L_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_Trq_x(:,1),K_10_R_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_Trq_x(:,1),K_transfer_L_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=transfer)');
subplot(5,2,8)
```

```
plot(K_transfer_R_Jt_Trq_x(:,1),K_transfer_R_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_Trq_x(:,1),K_worksite_L_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_Trq_x(:,1),K_worksite_R_Jt_Trq_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (Nm)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=worksite)');

figure(7)
subplot(5,2,1)
plot(K_max_L_Jt_State_x(:,1),K_max_L_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=MAX)');
subplot(5,2,2)
plot(K_max_R_Jt_State_x(:,1),K_max_R_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=MAX)');
subplot(5,2,3)
plot(K_250_L_Jt_State_x(:,1),K_250_L_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_State_x(:,1),K_250_R_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_State_x(:,1),K_10_L_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_State_x(:,1),K_10_R_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_State_x(:,1),K_transfer_L_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_State_x(:,1),K_transfer_R_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_State_x(:,1),K_worksite_L_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=worksite)');
subplot(5,2,10)
```

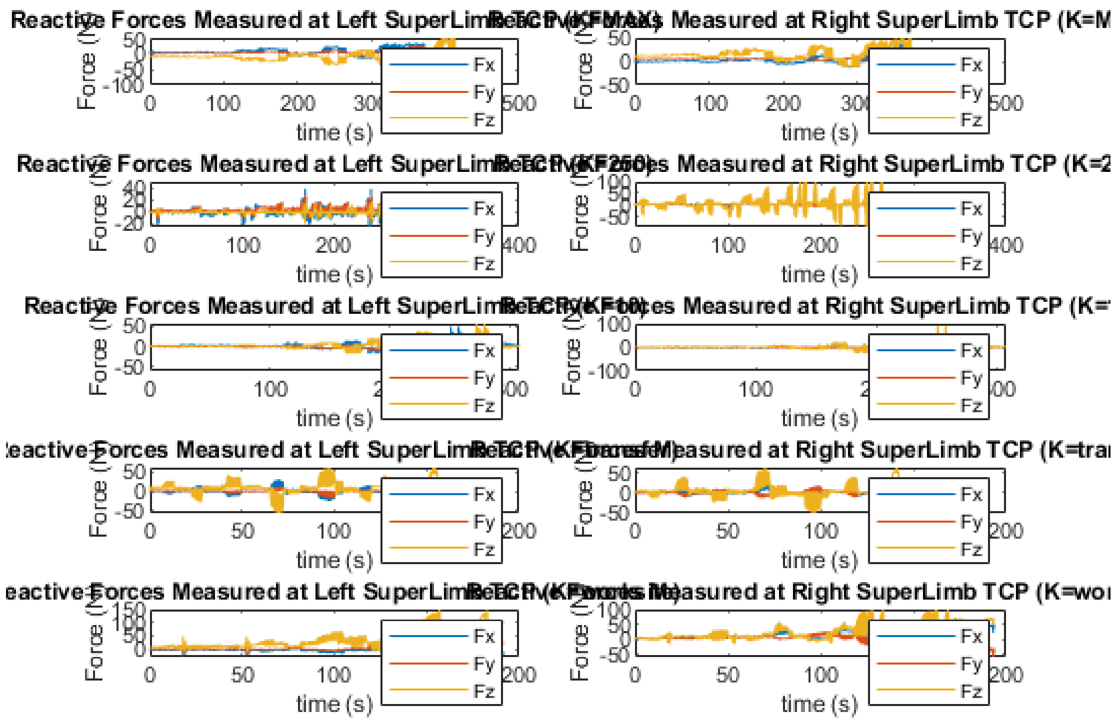
```
plot(K_worksite_R_Jt_State_x(:,1),K_worksite_R_Jt_State_x(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=worksite)');
```



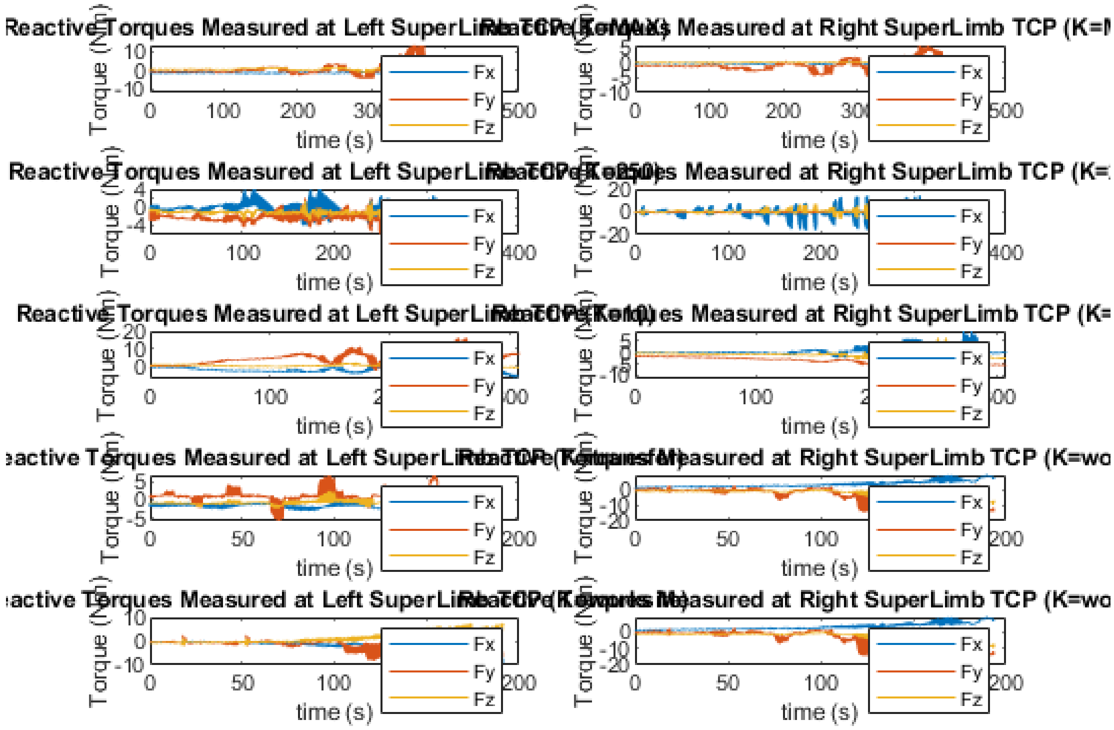


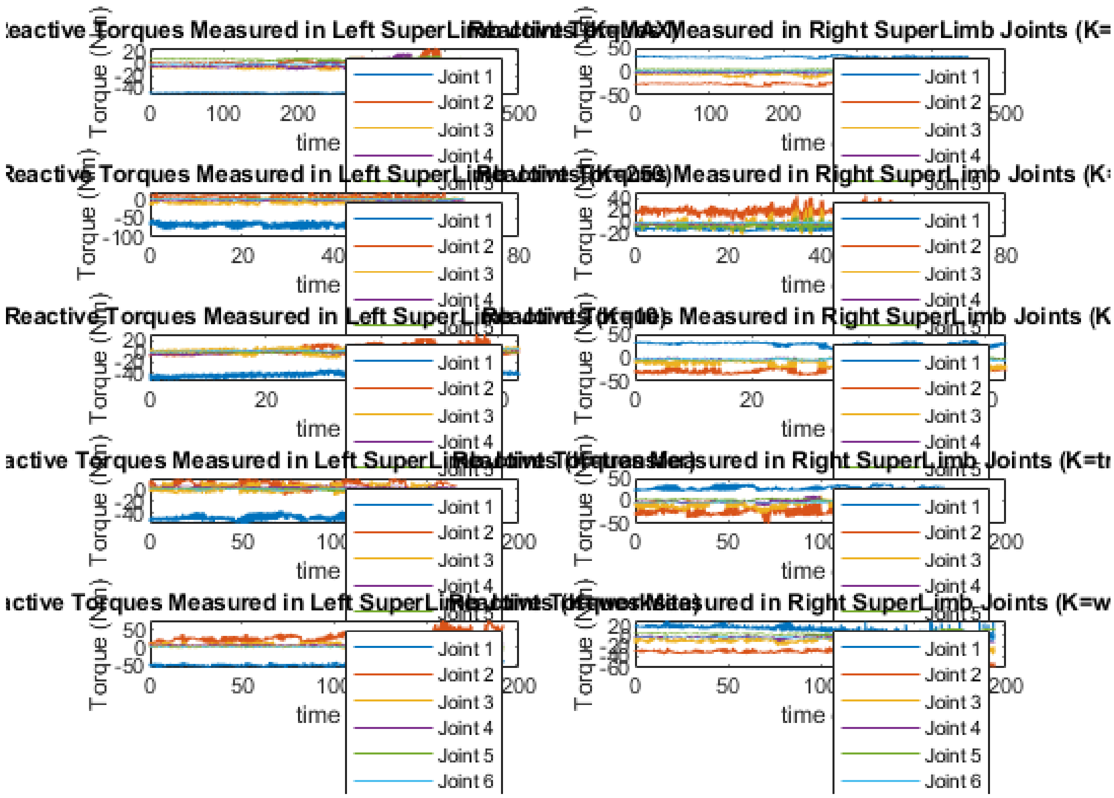


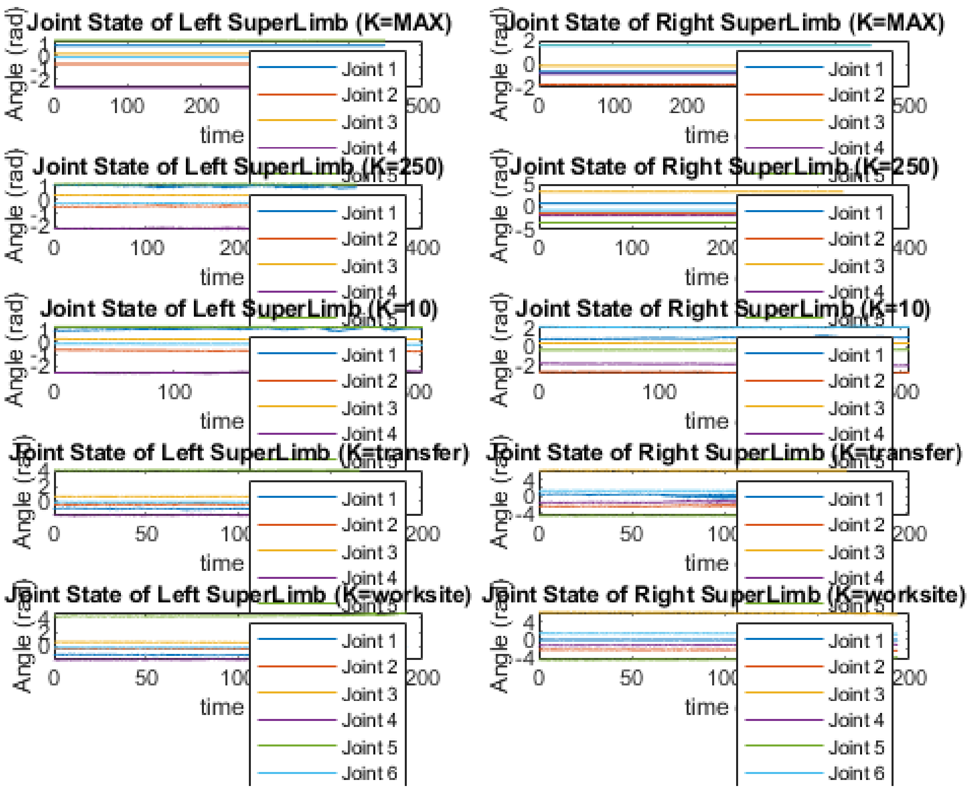
Reactive Load Measured at Right Handrail (K=MAX)
Reactive Load Measured at Right Handrail (K=250)
Reactive Load Measured at Right Handrail (K=10)
LC 1
LC 2
LC 3
LC 4



Fx
Fy
Fz
time (s)


Reactive Torques Measured at Left SuperLimb TCP
Reactive Torques Measured at Right SuperLimb TCP
Torque (Nm)
time (s)
Fx
Fy
Fz


Reactive Torques Measured in Left SuperLimb Joints
Reactive Torques Measured in Right SuperLimb Joints
Torque (Nm)
time
Joint 1
Joint 2
Joint 3
Joint 4
Joint 5
Joint 6



Y DIRECTION OPERATOR APPLIED FORCE %%

```
%%PROCESSING OF IMU AND OPERATION LOAD CELL DATA%%
K_max_IMU_LC_y = readmatrix("K_max_pose_2\IMU_LC_Data\test_y_1_1.csv");
K_250_IMU_LC_y = readmatrix("K_250_pose_4\IMU_LC_Data\test_y_3_1.csv");
K_10_IMU_LC_y = readmatrix("K_10_pose_3\IMU_LC_Data\test_y_2_1.csv");
K_transfer_IMU_LC_y = readmatrix("K_Transfer\IMU_LC_Data\Test_y.csv");
K_worksite_IMU_LC_y = readmatrix("K_Worksite\IMU_LC_Data\Test_y.csv");

K_max_IMU_y = [K_max_IMU_LC_y(:,3:6)];
K_250_IMU_y = [K_250_IMU_LC_y(:,3:6)];
K_10_IMU_y = [K_10_IMU_LC_y(:,3:6)];
K_transfer_IMU_y = [K_transfer_IMU_LC_y(:,3:6)];
K_worksite_IMU_y = [K_worksite_IMU_LC_y(:,3:6)];

K_max_LC_y = K_max_IMU_LC_y(:,2:3);
K_250_LC_y = K_250_IMU_LC_y(:,2:3);
K_10_LC_y = K_10_IMU_LC_y(:,2:3);
K_transfer_LC_y = K_transfer_IMU_LC_y(:,2:3);
K_worksite_LC_y = K_worksite_IMU_LC_y(:,2:3);

%%PLOT y OPERATOR LOAD CELL DATA%%
figure(1)
subplot(5,1,1)
plot(K_max_LC_y(:,1),K_max_LC_y(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=Max)');
subplot(5,1,2)
plot(K_250_LC_y(:,1),K_250_LC_y(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=250)');
subplot(5,1,3)
plot(K_10_LC_y(:,1),K_10_LC_y(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
```

```
title('Operator Load applied to MANTIS (K=10)');
subplot(5,1,4)
plot(K_transfer_LC_y(:,1),K_transfer_LC_y(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=transfer)');
subplot(5,1,5)
plot(K_worksite_LC_y(:,1),K_worksite_LC_y(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=worksite)');

%%PLOT IMU DATA%%
figure(2)
subplot(5,1,1)
plot(K_max_IMU_y(:,1),K_max_IMU_y(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=Max)');
subplot(5,1,2)
plot(K_250_IMU_y(:,1),K_250_IMU_y(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=250)');
subplot(5,1,3)
plot(K_10_IMU_y(:,1),K_10_IMU_y(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=10)');
subplot(5,1,4)
plot(K_transfer_IMU_y(:,1),K_transfer_IMU_y(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=transfer)');
subplot(5,1,5)
plot(K_worksite_IMU_y(:,1),K_worksite_IMU_y(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=worksite)');

%%PROCESSING OF HANDRAIL DATA%%
K_max_R_HR_y = readmatrix("K_max_pose_2\Handrail_Data\test_y_1_1_black.csv");
K_max_L_HR_y = readmatrix("K_max_pose_2\Handrail_Data\test_y_1_1_white.csv");
K_250_R_HR_y = readmatrix("K_250_pose_4\Handrail_Data\test_y_3_1_black.csv");
K_250_L_HR_y = readmatrix("K_250_pose_4\Handrail_Data\test_y_3_1_white.csv");
K_10_R_HR_y = readmatrix("K_10_pose_3\Handrail_Data\test_y_2_1_black.csv");
K_10_L_HR_y = readmatrix("K_10_pose_3\Handrail_Data\test_y_2_1_white.csv");
K_transfer_R_HR_y = readmatrix("K_Transfer\Handrail_Data\test_y_black.csv");
K_transfer_L_HR_y = readmatrix("K_Transfer\Handrail_Data\test_y_white.csv");
K_worksite_R_HR_y = readmatrix("K_Worksite\Handrail_Data\test_y_black.csv");
K_worksite_L_HR_y = readmatrix("K_Worksite\Handrail_Data\test_y_white.csv");

%%PLOT HANDRAIL DATA%%
figure(3)
subplot(5,2,1)
plot(K_max_L_HR_y(:,1),K_max_L_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=Max)');
subplot(5,2,2)
plot(K_max_R_HR_y(:,1),K_max_R_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=Max)');
```

```
subplot(5,2,3)
plot(K_250_L_HR_y(:,1),K_250_L_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=250)');
subplot(5,2,4)
plot(K_250_R_HR_y(:,1),K_250_R_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=250)');
subplot(5,2,5)
plot(K_10_L_HR_y(:,1),K_10_L_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=10)');
subplot(5,2,6)
plot(K_10_R_HR_y(:,1),K_10_R_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=10)');
subplot(5,2,7)
plot(K_transfer_L_HR_y(:,1),K_transfer_L_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_HR_y(:,1),K_transfer_R_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_HR_y(:,1),K_worksite_L_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_HR_y(:,1),K_worksite_R_HR_y(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=worksite)');

%%PROCESSING OF UR5E DATA%%
K_max_R_FT_y = readmatrix("K_max_pose_2\UR5e_Data\test_y_1_1\right_ft_data.csv");
K_max_L_FT_y = readmatrix("K_max_pose_2\UR5e_Data\test_y_1_1\left_ft_data.csv");
K_250_R_FT_y = readmatrix("K_250_pose_4\UR5e_Data\test_y_3_1\right_ft_data.csv");
K_250_L_FT_y = readmatrix("K_250_pose_4\UR5e_Data\test_y_3_1\left_ft_data.csv");
K_10_R_FT_y = readmatrix("K_10_pose_3\UR5e_Data\test_y_2_1\right_ft_data.csv");
K_10_L_FT_y = readmatrix("K_10_pose_3\UR5e_Data\test_y_2_1\left_ft_data.csv");
K_transfer_R_FT_y = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Y\right_ft_data.csv");
K_transfer_L_FT_y = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Y\left_ft_data.csv");
K_worksite_R_FT_y = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Y\right_ft_data.csv");
K_worksite_L_FT_y = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Y\left_ft_data.csv");

K_max_R_FT_y = [K_max_R_FT_y(:,3),K_max_R_FT_y(:,5:10)];
K_max_L_FT_y = [K_max_L_FT_y(:,3),K_max_L_FT_y(:,5:10)];
K_250_R_FT_y = [K_250_R_FT_y(:,3),K_250_R_FT_y(:,5:10)];
K_250_L_FT_y = [K_250_L_FT_y(:,3),K_250_L_FT_y(:,5:10)];
K_10_R_FT_y = [K_10_R_FT_y(:,3),K_10_R_FT_y(:,5:10)];
K_10_L_FT_y = [K_10_L_FT_y(:,3),K_10_L_FT_y(:,5:10)];
K_transfer_R_FT_y = [K_transfer_R_FT_y(:,3),K_transfer_R_FT_y(:,5:10)];
K_transfer_L_FT_y = [K_transfer_L_FT_y(:,3),K_transfer_L_FT_y(:,5:10)];
K_worksite_R_FT_y = [K_worksite_R_FT_y(:,3),K_worksite_R_FT_y(:,5:10)];
```

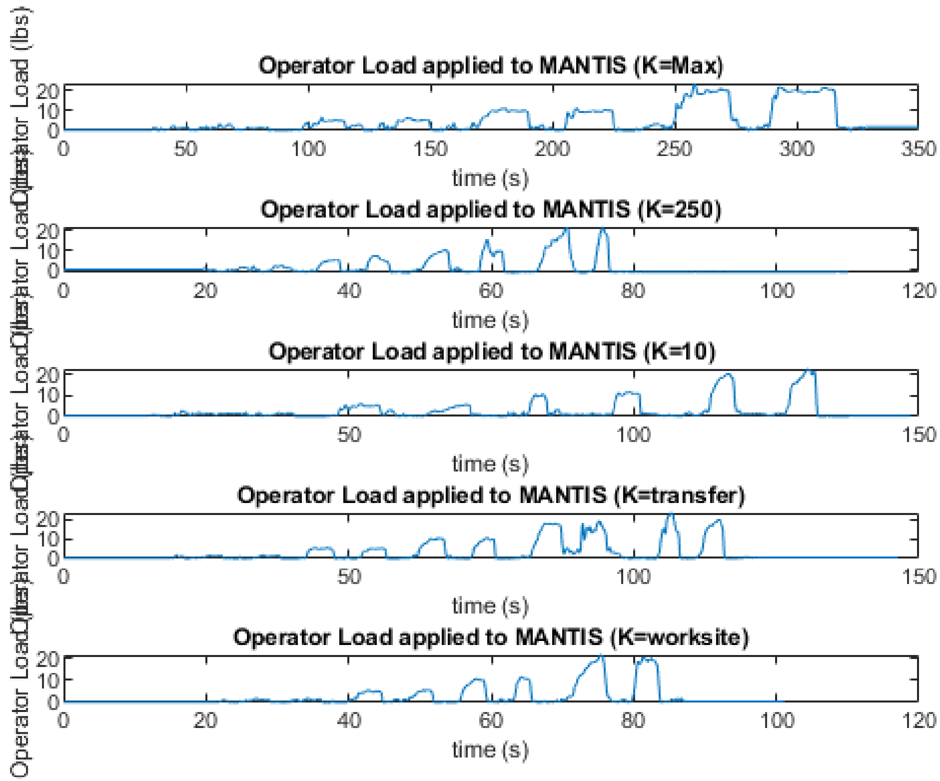
```
K_worksite_L_FT_y = [K_worksite_L_FT_y(:,3),K_worksite_L_FT_y(:,5:10)];

K_max_R_Jt_Trq_y = readmatrix("K_max_pose_2\UR5e_Data\test_y_1_1\right_joint_torques.csv");
K_max_L_Jt_Trq_y = readmatrix("K_max_pose_2\UR5e_Data\test_y_1_1\left_joint_torques.csv");
K_250_R_Jt_Trq_y = readmatrix("K_250_pose_4\UR5e_Data\test_y_3_1\right_joint_torques.csv");
K_250_L_Jt_Trq_y = readmatrix("K_250_pose_4\UR5e_Data\test_y_3_1\left_joint_torques.csv");
K_10_R_Jt_Trq_y = readmatrix("K_10_pose_3\UR5e_Data\test_y_2_1\right_joint_torques.csv");
K_10_L_Jt_Trq_y = readmatrix("K_10_pose_3\UR5e_Data\test_y_2_1\left_joint_torques.csv");
K_transfer_R_Jt_Trq_y = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Y\right_joint_torques.csv");
K_transfer_L_Jt_Trq_y = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Y\left_joint_torques.csv");
K_worksite_R_Jt_Trq_y = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Y\right_joint_torques.csv");
K_worksite_L_Jt_Trq_y = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Y\left_joint_torques.csv");

K_max_R_Jt_Trq_y = K_max_R_Jt_Trq_y(:,2:8);
K_max_L_Jt_Trq_y = K_max_L_Jt_Trq_y(:,2:8);
K_250_R_Jt_Trq_y = K_250_R_Jt_Trq_y(:,2:8);
K_250_L_Jt_Trq_y = K_250_L_Jt_Trq_y(:,2:8);
K_10_R_Jt_Trq_y = K_10_R_Jt_Trq_y(:,2:8);
K_10_L_Jt_Trq_y = K_10_L_Jt_Trq_y(:,2:8);
K_transfer_R_Jt_Trq_y = K_transfer_R_Jt_Trq_y(:,2:8);
K_transfer_L_Jt_Trq_y = K_transfer_L_Jt_Trq_y(:,2:8);
K_worksite_R_Jt_Trq_y = K_worksite_R_Jt_Trq_y(:,2:8);
K_worksite_L_Jt_Trq_y = K_worksite_L_Jt_Trq_y(:,2:8);

K_max_R_Jt_State_y = readmatrix("K_max_pose_2\UR5e_Data\test_y_1_1\right_joint_states.csv");
K_max_L_Jt_State_y = readmatrix("K_max_pose_2\UR5e_Data\test_y_1_1\left_joint_states.csv");
K_250_R_Jt_State_y = readmatrix("K_250_pose_4\UR5e_Data\test_y_3_1\right_joint_states.csv");
K_250_L_Jt_State_y = readmatrix("K_250_pose_4\UR5e_Data\test_y_3_1\left_joint_states.csv");
K_10_R_Jt_State_y = readmatrix("K_10_pose_3\UR5e_Data\test_y_2_1\right_joint_states.csv");
K_10_L_Jt_State_y = readmatrix("K_10_pose_3\UR5e_Data\test_y_2_1\left_joint_states.csv");
K_transfer_R_Jt_State_y = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Y\right_joint_states.csv");
K_transfer_L_Jt_State_y = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Y\left_joint_states.csv");
K_worksite_R_Jt_State_y = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Y\right_joint_states.csv");
K_worksite_L_Jt_State_y = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Y\left_joint_states.csv");

K_max_R_Jt_State_y = [K_max_R_Jt_State_y(:,3),K_max_R_Jt_State_y(:,10:15)];
K_max_L_Jt_State_y = [K_max_L_Jt_State_y(:,3),K_max_L_Jt_State_y(:,10:15)];
K_250_R_Jt_State_y = [K_250_R_Jt_State_y(:,3),K_250_R_Jt_State_y(:,10:15)];
K_250_L_Jt_State_y = [K_250_L_Jt_State_y(:,3),K_250_L_Jt_State_y(:,10:15)];
K_10_R_Jt_State_y = [K_10_R_Jt_State_y(:,3),K_10_R_Jt_State_y(:,10:15)];
K_10_L_Jt_State_y = [K_10_L_Jt_State_y(:,3),K_10_L_Jt_State_y(:,10:15)];
K_transfer_R_Jt_State_y = [K_transfer_R_Jt_State_y(:,3),K_transfer_R_Jt_State_y(:,10:15)];
K_transfer_L_Jt_State_y = [K_transfer_L_Jt_State_y(:,3),K_transfer_L_Jt_State_y(:,10:15)];
K_worksite_R_Jt_State_y = [K_worksite_R_Jt_State_y(:,3),K_worksite_R_Jt_State_y(:,10:15)];
K_worksite_L_Jt_State_y = [K_worksite_L_Jt_State_y(:,3),K_worksite_L_Jt_State_y(:,10:15)];

%%PLOT UR5E DATA%%
figure(4)
subplot(5,2,1)
plot(K_max_L_FT_y(:,1),K_max_L_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_y(:,1),K_max_R_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_y(:,1),K_250_L_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
```

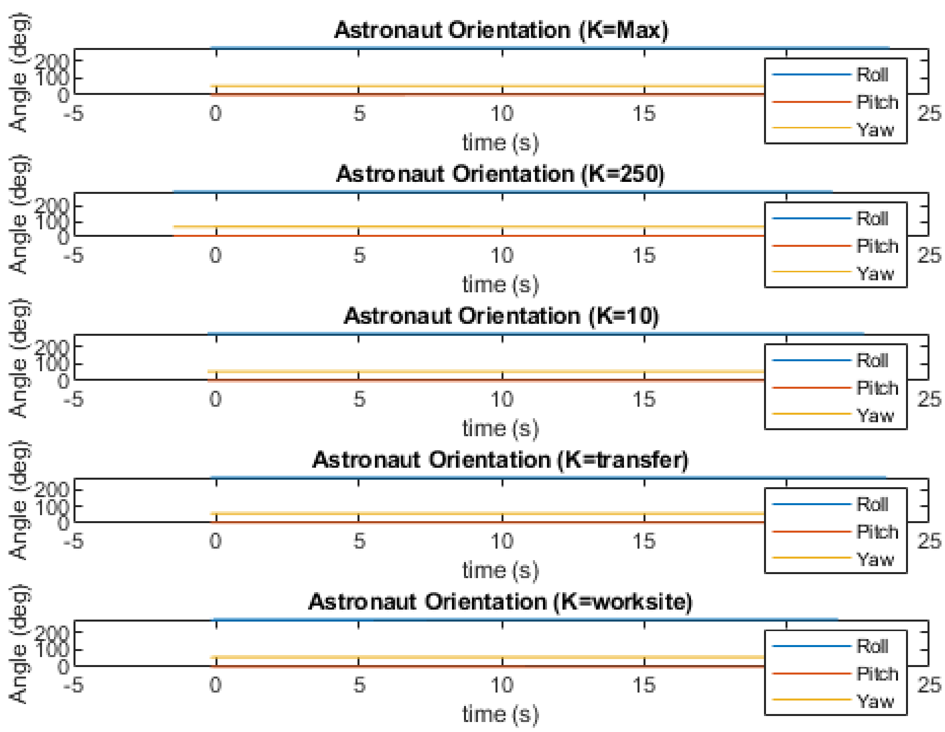
```
title('Reactive Forces Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_y(:,1),K_250_R_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_y(:,1),K_10_L_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_y(:,1),K_10_R_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_y(:,1),K_transfer_L_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_FT_y(:,1),K_transfer_R_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_FT_y(:,1),K_worksite_L_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_y(:,1),K_worksite_R_FT_y(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=worksite)');

figure(5)
subplot(5,2,1)
plot(K_max_L_FT_y(:,1),K_max_L_FT_y(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_y(:,1),K_max_R_FT_y(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_y(:,1),K_250_L_FT_y(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_y(:,1),K_250_R_FT_y(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_y(:,1),K_10_L_FT_y(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
```

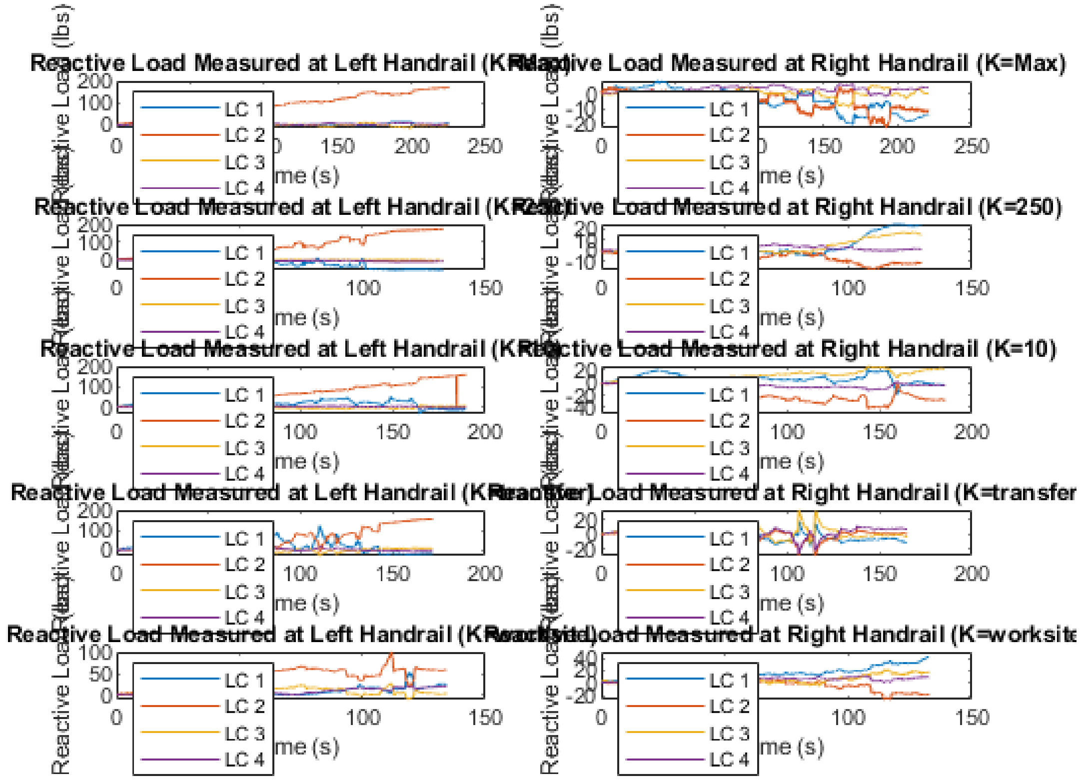
```
title('Reactive Torques Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_y(:,1),K_10_R_FT_y(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_y(:,1),K_transfer_L_FT_y(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_worksite_R_FT_y(:,1),K_worksite_R_FT_y(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');
subplot(5,2,9)
plot(K_worksite_L_FT_y(:,1),K_worksite_L_FT_y(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_y(:,1),K_worksite_R_FT_y(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');

figure(6)
subplot(5,2,1)
plot(K_max_L_Jt_Trq_y(:,1),K_max_L_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_Trq_y(:,1),K_max_R_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_Trq_y(:,1),K_250_L_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_Trq_y(:,1),K_250_R_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_Trq_y(:,1),K_10_L_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_Trq_y(:,1),K_10_R_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_Trq_y(:,1),K_transfer_L_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
```

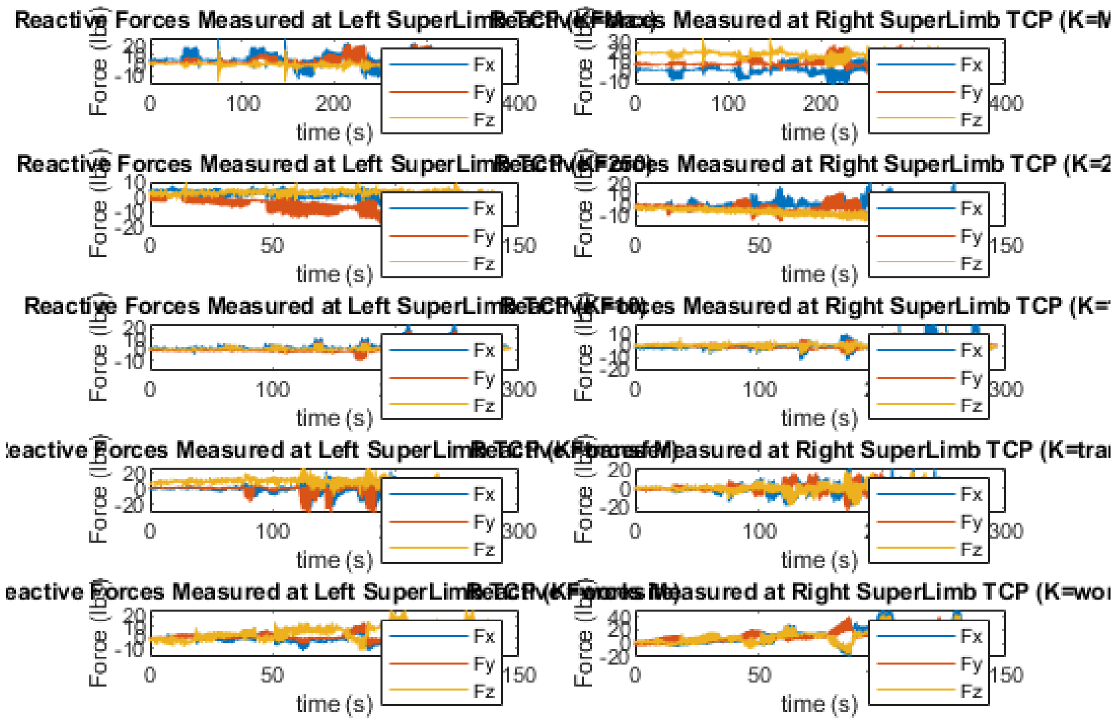
```
title('Reactive Torques Measured in Left SuperLimb Joints (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_Trq_y(:,1),K_transfer_R_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_Trq_y(:,1),K_worksite_L_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_Trq_y(:,1),K_worksite_R_Jt_Trq_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=worksite)');

figure(7)
subplot(5,2,1)
plot(K_max_L_Jt_State_y(:,1),K_max_L_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_State_y(:,1),K_max_R_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_State_y(:,1),K_250_L_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_State_y(:,1),K_250_R_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_State_y(:,1),K_10_L_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_State_y(:,1),K_10_R_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_State_y(:,1),K_transfer_L_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_State_y(:,1),K_transfer_R_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_State_y(:,1),K_worksite_L_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
```

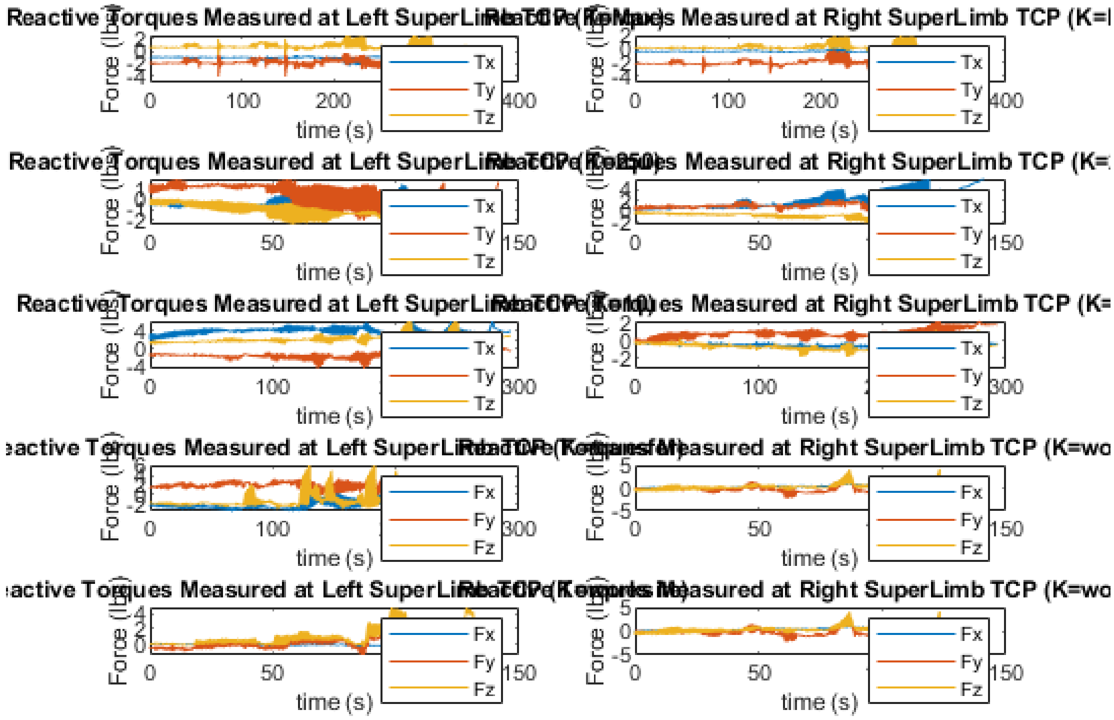
```
title('Joint State of Left SuperLimb (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_State_y(:,1),K_worksite_R_Jt_State_y(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=worksite)');
```


Operator Load applied to MANTIS (K=Max)
Operator Load (lbs)
time (s)
Operator Load applied to MANTIS (K=250)
Operator Load applied to MANTIS (K=10)
Operator Load applied to MANTIS (K=transfer)
Operator Load applied to MANTIS (K=worksite)

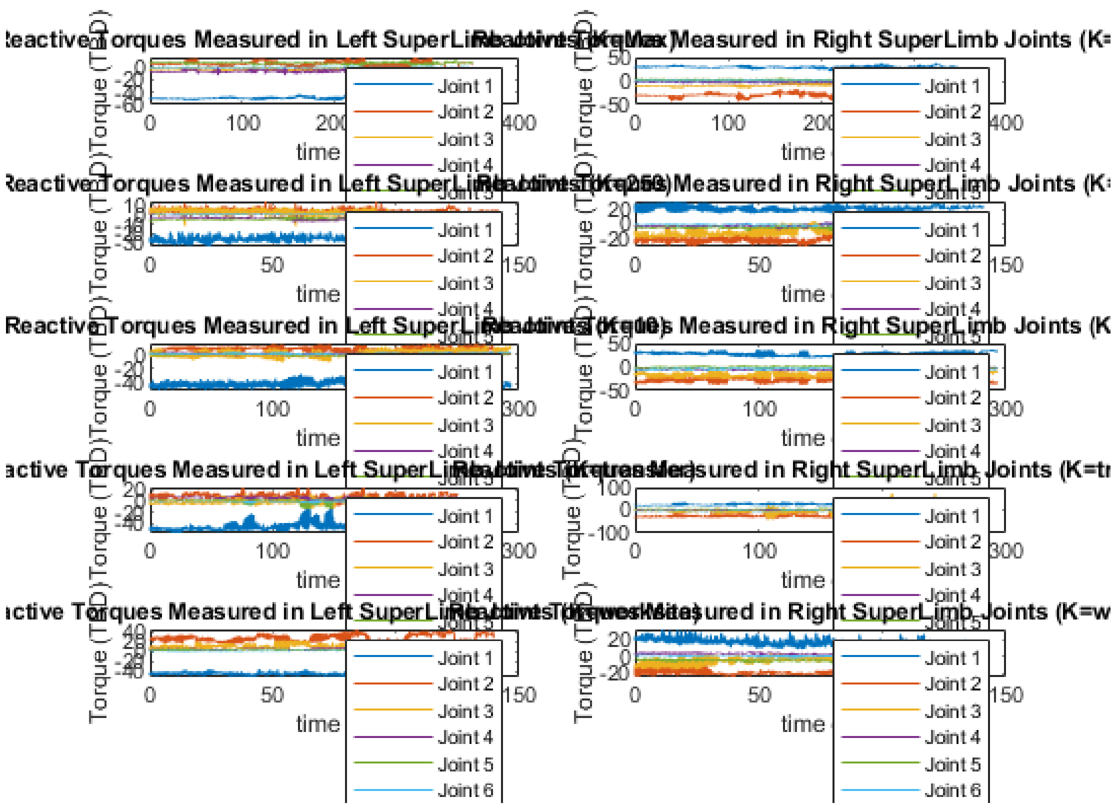

Astronaut Orientation (K=Max)
Astronaut Orientation (K=250)
Astronaut Orientation (K=10)
Astronaut Orientation (K=transfer)
Astronaut Orientation (K=worksite)
Angle (deg)
time (s)
Roll
Pitch
Yaw


Reactive Load Measured at Right Handrail (K=Max)
Reactive Load Measured at Right Handrail (K=250)
Reactive Load Measured at Right Handrail (K=10)
Reactive Load (lbs)
time (s)
LC 1
LC 2
LC 3
LC 4

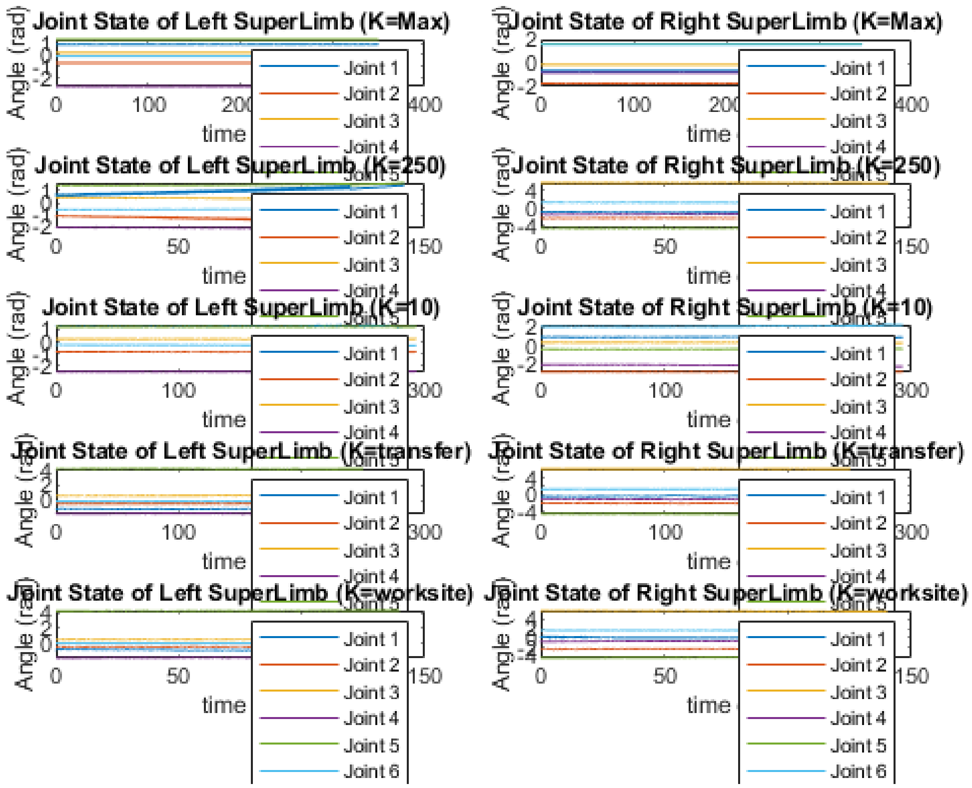

Force (lbs)
time (s)
Fx
Fy
Fz



Reactive Torques Measured at Right SuperLimb TCP
time (s)
Tx
Ty
Tz
Fx
Fy
Fz



Measured in Right SuperLimb Joints
time
Joint 1
Joint 2
Joint 3
Joint 4
Joint 5
Joint 6



Z DIRECTION OPERATOR APPLIED FORCE %%

```
%%PROCESSING OF IMU AND OPERATION LOAD CELL DATA%%
K_max_IMU_LC_z = readmatrix("K_max_pose_2\IMU_LC_Data\test_z_1_1.csv");
K_250_IMU_LC_z = readmatrix("K_250_pose_4\IMU_LC_Data\test_z_3_1.csv");
K_10_IMU_LC_z = readmatrix("K_10_pose_3\IMU_LC_Data\test_z_2_1.csv");
K_transfer_IMU_LC_z = readmatrix("K_Transfer\IMU_LC_Data\Test_z.csv");
K_worksite_IMU_LC_z = readmatrix("K_Worksite\IMU_LC_Data\Test_z.csv");

K_max_IMU_z = [K_max_IMU_LC_z(:,3:6)];
K_250_IMU_z = [K_250_IMU_LC_z(:,3:6)];
K_10_IMU_z = [K_10_IMU_LC_z(:,3:6)];
K_transfer_IMU_z = [K_transfer_IMU_LC_z(:,3:6)];
K_worksite_IMU_z = [K_worksite_IMU_LC_z(:,3:6)];

K_max_LC_z = K_max_IMU_LC_z(:,2:3);
K_250_LC_z = K_250_IMU_LC_z(:,2:3);
K_10_LC_z = K_10_IMU_LC_z(:,2:3);
K_transfer_LC_z = K_transfer_IMU_LC_z(:,2:3);
K_worksite_LC_z = K_worksite_IMU_LC_z(:,2:3);

%%PLOT z OPERATOR LOAD CELL DATA%%
figure(1)
subplot(5,1,1)
plot(K_max_LC_z(:,1),K_max_LC_z(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=Max)');
subplot(5,1,2)
plot(K_250_LC_z(:,1),K_250_LC_z(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=250)');
subplot(5,1,3)
plot(K_10_LC_z(:,1),K_10_LC_z(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
```

```
title('Operator Load applied to MANTIS (K=10)');
subplot(5,1,4)
plot(K_transfer_LC_z(:,1),K_transfer_LC_z(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=transfer)');
subplot(5,1,5)
plot(K_worksite_LC_z(:,1),K_worksite_LC_z(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=worksite)');

%%PLOT IMU DATA%%
figure(2)
subplot(5,1,1)
plot(K_max_IMU_z(:,1),K_max_IMU_z(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=Max)');
subplot(5,1,2)
plot(K_250_IMU_z(:,1),K_250_IMU_z(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=250)');
subplot(5,1,3)
plot(K_10_IMU_z(:,1),K_10_IMU_z(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=10)');
subplot(5,1,4)
plot(K_transfer_IMU_z(:,1),K_transfer_IMU_z(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=transfer)');
subplot(5,1,5)
plot(K_worksite_IMU_z(:,1),K_worksite_IMU_z(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=worksite)');

%%PROCESSING OF HANDRAIL DATA%%
K_max_R_HR_z = readmatrix("K_max_pose_2\Handrail_Data\test_z_1_1_black.csv");
K_max_L_HR_z = readmatrix("K_max_pose_2\Handrail_Data\test_z_1_1_white.csv");
K_250_R_HR_z = readmatrix("K_250_pose_4\Handrail_Data\test_z_3_1_black.csv");
K_250_L_HR_z = readmatrix("K_250_pose_4\Handrail_Data\test_z_3_1_white.csv");
K_10_R_HR_z = readmatrix("K_10_pose_3\Handrail_Data\test_z_2_1_black.csv");
K_10_L_HR_z = readmatrix("K_10_pose_3\Handrail_Data\test_z_2_1_white.csv");
K_transfer_R_HR_z = readmatrix("K_Transfer\Handrail_Data\test_z_black.csv");
K_transfer_L_HR_z = readmatrix("K_Transfer\Handrail_Data\test_z_white.csv");
K_worksite_R_HR_z = readmatrix("K_Worksite\Handrail_Data\test_z_black.csv");
K_worksite_L_HR_z = readmatrix("K_Worksite\Handrail_Data\test_z_white.csv");

%%PLOT HANDRAIL DATA%%
figure(3)
subplot(5,2,1)
plot(K_max_L_HR_z(:,1),K_max_L_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=Max)');
subplot(5,2,2)
plot(K_max_R_HR_z(:,1),K_max_R_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=Max)');
```

```
subplot(5,2,3)
plot(K_250_L_HR_z(:,1),K_250_L_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=250)');
subplot(5,2,4)
plot(K_250_R_HR_z(:,1),K_250_R_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=250)');
subplot(5,2,5)
plot(K_10_L_HR_z(:,1),K_10_L_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=10)');
subplot(5,2,6)
plot(K_10_R_HR_z(:,1),K_10_R_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=10)');
subplot(5,2,7)
plot(K_transfer_L_HR_z(:,1),K_transfer_L_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_HR_z(:,1),K_transfer_R_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_HR_z(:,1),K_worksite_L_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_HR_z(:,1),K_worksite_R_HR_z(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=worksite)');

%%PROCESSING OF UR5E DATA%%
K_max_R_FT_z = readmatrix("K_max_pose_2\UR5e_Data\test_z_1_1\right_ft_data.csv");
K_max_L_FT_z = readmatrix("K_max_pose_2\UR5e_Data\test_z_1_1\left_ft_data.csv");
K_250_R_FT_z = readmatrix("K_250_pose_4\UR5e_Data\test_z_3_1\right_ft_data.csv");
K_250_L_FT_z = readmatrix("K_250_pose_4\UR5e_Data\test_z_3_1\left_ft_data.csv");
K_10_R_FT_z = readmatrix("K_10_pose_3\UR5e_Data\test_z_2_1\right_ft_data.csv");
K_10_L_FT_z = readmatrix("K_10_pose_3\UR5e_Data\test_z_2_1\left_ft_data.csv");
K_transfer_R_FT_z = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Z\right_ft_data.csv");
K_transfer_L_FT_z = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Z\left_ft_data.csv");
K_worksite_R_FT_z = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Z\right_ft_data.csv");
K_worksite_L_FT_z = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Z\left_ft_data.csv");

K_max_R_FT_z = [K_max_R_FT_z(:,3),K_max_R_FT_z(:,5:10)];
K_max_L_FT_z = [K_max_L_FT_z(:,3),K_max_L_FT_z(:,5:10)];
K_250_R_FT_z = [K_250_R_FT_z(:,3),K_250_R_FT_z(:,5:10)];
K_250_L_FT_z = [K_250_L_FT_z(:,3),K_250_L_FT_z(:,5:10)];
K_10_R_FT_z = [K_10_R_FT_z(:,3),K_10_R_FT_z(:,5:10)];
K_10_L_FT_z = [K_10_L_FT_z(:,3),K_10_L_FT_z(:,5:10)];
K_transfer_R_FT_z = [K_transfer_R_FT_z(:,3),K_transfer_R_FT_z(:,5:10)];
K_transfer_L_FT_z = [K_transfer_L_FT_z(:,3),K_transfer_L_FT_z(:,5:10)];
K_worksite_R_FT_z = [K_worksite_R_FT_z(:,3),K_worksite_R_FT_z(:,5:10)];
```

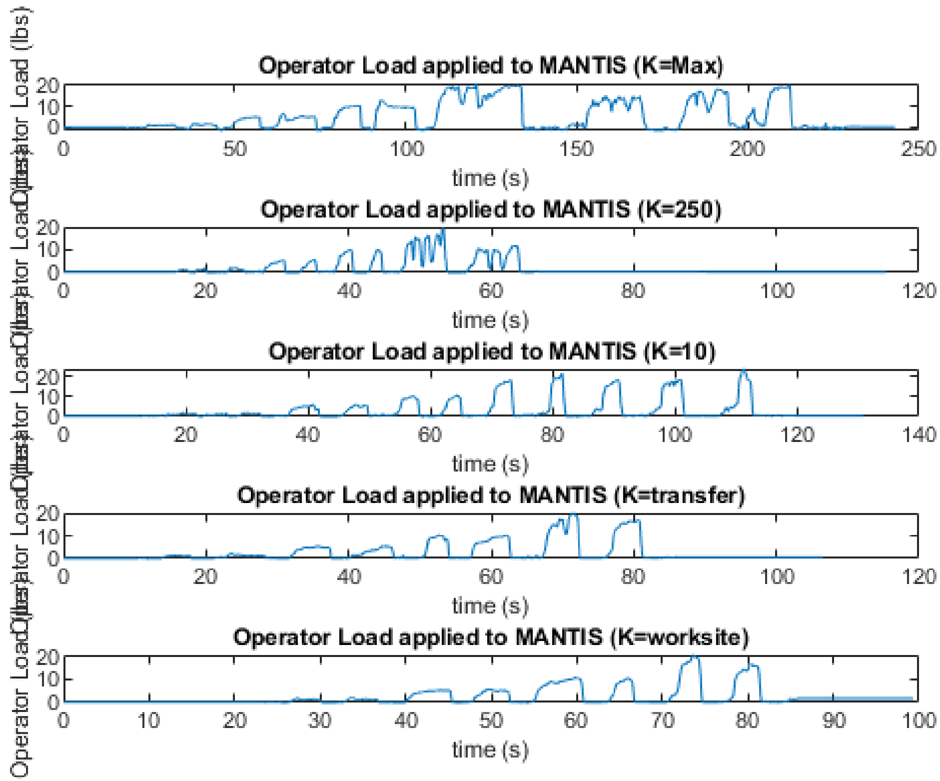
```
K_worksite_L_FT_z = [K_worksite_L_FT_z(:,3),K_worksite_L_FT_z(:,5:10)];

K_max_R_Jt_Trq_z = readmatrix("K_max_pose_2\UR5e_Data\test_z_1_1\right_joint_torques.csv");
K_max_L_Jt_Trq_z = readmatrix("K_max_pose_2\UR5e_Data\test_z_1_1\left_joint_torques.csv");
K_250_R_Jt_Trq_z = readmatrix("K_250_pose_4\UR5e_Data\test_z_3_1\right_joint_torques.csv");
K_250_L_Jt_Trq_z = readmatrix("K_250_pose_4\UR5e_Data\test_z_3_1\left_joint_torques.csv");
K_10_R_Jt_Trq_z = readmatrix("K_10_pose_3\UR5e_Data\test_z_2_1\right_joint_torques.csv");
K_10_L_Jt_Trq_z = readmatrix("K_10_pose_3\UR5e_Data\test_z_2_1\left_joint_torques.csv");
K_transfer_R_Jt_Trq_z = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Z\right_joint_torques.csv");
K_transfer_L_Jt_Trq_z = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Z\left_joint_torques.csv");
K_worksite_R_Jt_Trq_z = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Z\right_joint_torques.csv");
K_worksite_L_Jt_Trq_z = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Z\left_joint_torques.csv");

K_max_R_Jt_Trq_z = K_max_R_Jt_Trq_z(:,2:8);
K_max_L_Jt_Trq_z = K_max_L_Jt_Trq_z(:,2:8);
K_250_R_Jt_Trq_z = K_250_R_Jt_Trq_z(:,2:8);
K_250_L_Jt_Trq_z = K_250_L_Jt_Trq_z(:,2:8);
K_10_R_Jt_Trq_z = K_10_R_Jt_Trq_z(:,2:8);
K_10_L_Jt_Trq_z = K_10_L_Jt_Trq_z(:,2:8);
K_transfer_R_Jt_Trq_z = K_transfer_R_Jt_Trq_z(:,2:8);
K_transfer_L_Jt_Trq_z = K_transfer_L_Jt_Trq_z(:,2:8);
K_worksite_R_Jt_Trq_z = K_worksite_R_Jt_Trq_z(:,2:8);
K_worksite_L_Jt_Trq_z = K_worksite_L_Jt_Trq_z(:,2:8);

K_max_R_Jt_State_z = readmatrix("K_max_pose_2\UR5e_Data\test_z_1_1\right_joint_states.csv");
K_max_L_Jt_State_z = readmatrix("K_max_pose_2\UR5e_Data\test_z_1_1\left_joint_states.csv");
K_250_R_Jt_State_z = readmatrix("K_250_pose_4\UR5e_Data\test_z_3_1\right_joint_states.csv");
K_250_L_Jt_State_z = readmatrix("K_250_pose_4\UR5e_Data\test_z_3_1\left_joint_states.csv");
K_10_R_Jt_State_z = readmatrix("K_10_pose_3\UR5e_Data\test_z_2_1\right_joint_states.csv");
K_10_L_Jt_State_z = readmatrix("K_10_pose_3\UR5e_Data\test_z_2_1\left_joint_states.csv");
K_transfer_R_Jt_State_z = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Z\right_joint_states.csv");
K_transfer_L_Jt_State_z = readmatrix("K_Transfer\UR5e_Data\K_Transfer_Z\left_joint_states.csv");
K_worksite_R_Jt_State_z = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Z\right_joint_states.csv");
K_worksite_L_Jt_State_z = readmatrix("K_Worksite\UR5e_Data\K_Worksite_Z\left_joint_states.csv");

K_max_R_Jt_State_z = [K_max_R_Jt_State_z(:,3),K_max_R_Jt_State_z(:,10:15)];
K_max_L_Jt_State_z = [K_max_L_Jt_State_z(:,3),K_max_L_Jt_State_z(:,10:15)];
K_250_R_Jt_State_z = [K_250_R_Jt_State_z(:,3),K_250_R_Jt_State_z(:,10:15)];
K_250_L_Jt_State_z = [K_250_L_Jt_State_z(:,3),K_250_L_Jt_State_z(:,10:15)];
K_10_R_Jt_State_z = [K_10_R_Jt_State_z(:,3),K_10_R_Jt_State_z(:,10:15)];
K_10_L_Jt_State_z = [K_10_L_Jt_State_z(:,3),K_10_L_Jt_State_z(:,10:15)];
K_transfer_R_Jt_State_z = [K_transfer_R_Jt_State_z(:,3),K_transfer_R_Jt_State_z(:,10:15)];
K_transfer_L_Jt_State_z = [K_transfer_L_Jt_State_z(:,3),K_transfer_L_Jt_State_z(:,10:15)];
K_worksite_R_Jt_State_z = [K_worksite_R_Jt_State_z(:,3),K_worksite_R_Jt_State_z(:,10:15)];
K_worksite_L_Jt_State_z = [K_worksite_L_Jt_State_z(:,3),K_worksite_L_Jt_State_z(:,10:15)];

%%PLOT UR5E DATA%%
figure(4)
subplot(5,2,1)
plot(K_max_L_FT_z(:,1),K_max_L_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_z(:,1),K_max_R_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_z(:,1),K_250_L_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
```

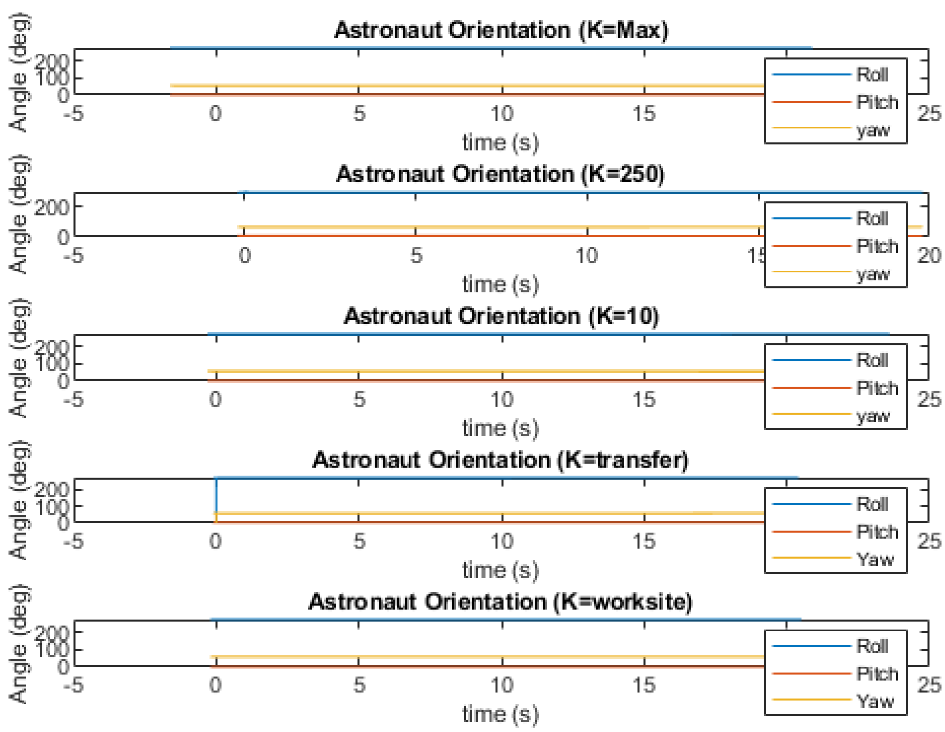
```
title('Reactive Forces Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_z(:,1),K_250_R_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_z(:,1),K_10_L_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_z(:,1),K_10_R_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_z(:,1),K_transfer_L_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_FT_z(:,1),K_transfer_R_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_FT_z(:,1),K_worksite_L_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_z(:,1),K_worksite_R_FT_z(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=worksite)');

figure(5)
subplot(5,2,1)
plot(K_max_L_FT_z(:,1),K_max_L_FT_z(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_z(:,1),K_max_R_FT_z(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_z(:,1),K_250_L_FT_z(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_z(:,1),K_250_R_FT_z(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_z(:,1),K_10_L_FT_z(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
```

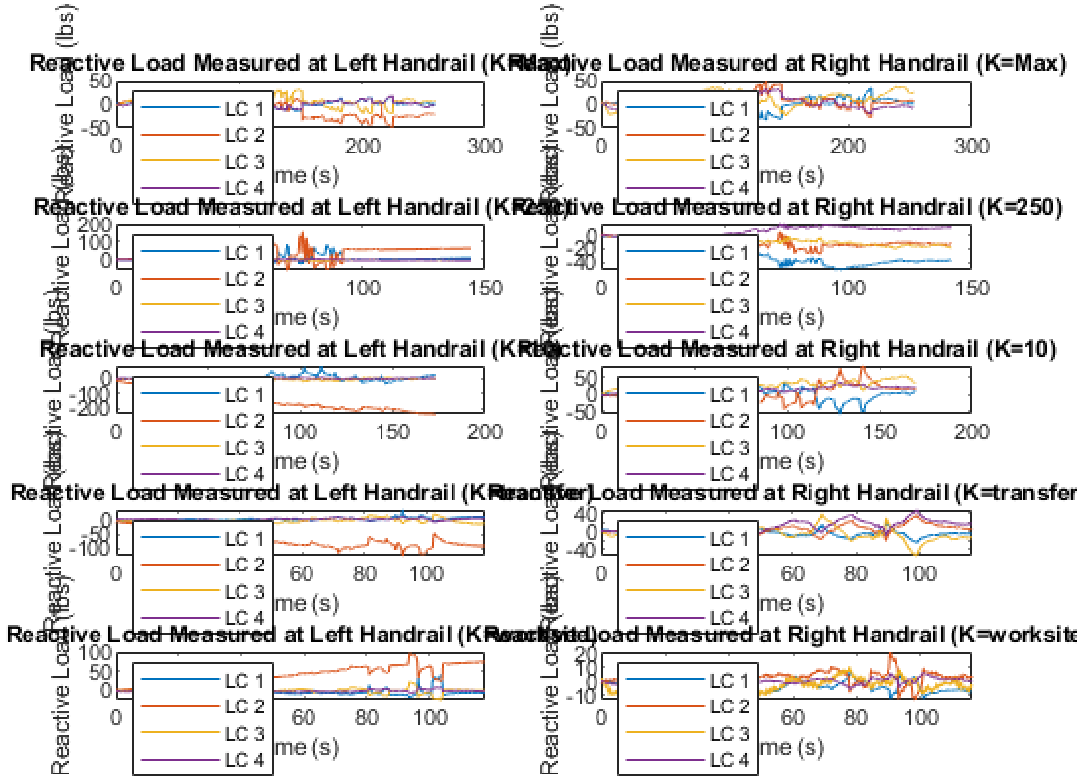
```
title('Reactive Torques Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_z(:,1),K_10_R_FT_z(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_z(:,1),K_transfer_L_FT_z(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_worksite_R_FT_z(:,1),K_worksite_R_FT_z(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');
subplot(5,2,9)
plot(K_worksite_L_FT_z(:,1),K_worksite_L_FT_z(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_z(:,1),K_worksite_R_FT_z(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');

figure(6)
subplot(5,2,1)
plot(K_max_L_Jt_Trq_z(:,1),K_max_L_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_Trq_z(:,1),K_max_R_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_Trq_z(:,1),K_250_L_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_Trq_z(:,1),K_250_R_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_Trq_z(:,1),K_10_L_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_Trq_z(:,1),K_10_R_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_Trq_z(:,1),K_transfer_L_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
```

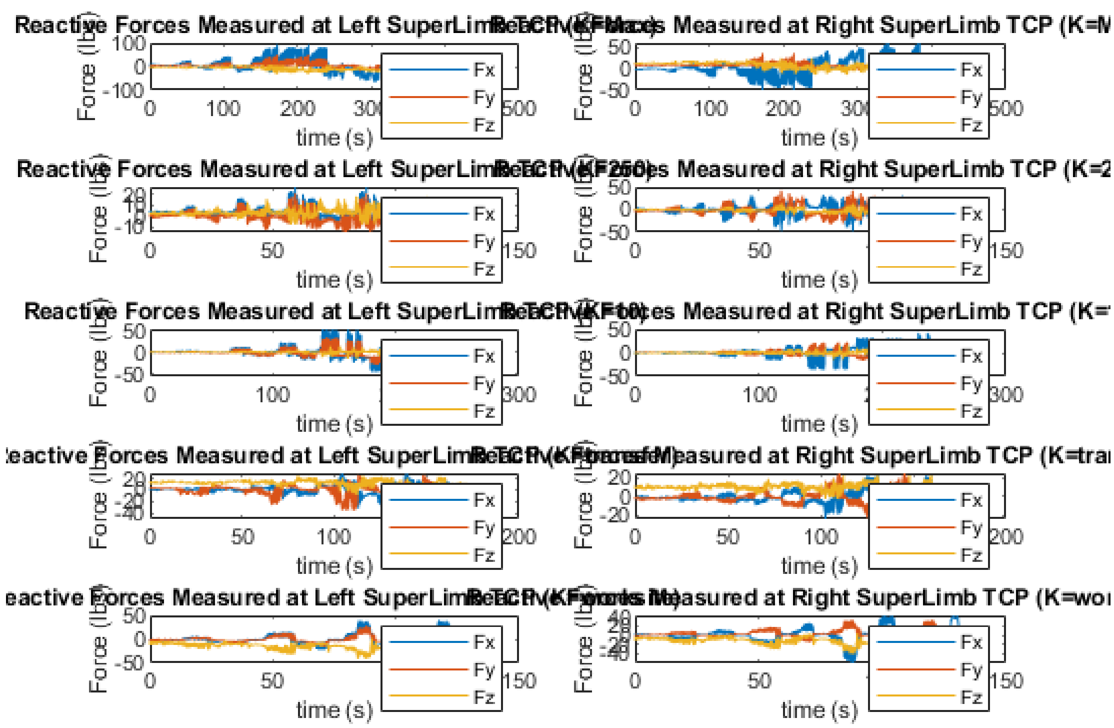
```
title('Reactive Torques Measured in Left SuperLimb Joints (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_Trq_z(:,1),K_transfer_R_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_Trq_z(:,1),K_worksite_L_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_Trq_z(:,1),K_worksite_R_Jt_Trq_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=worksite)');

figure(7)
subplot(5,2,1)
plot(K_max_L_Jt_State_z(:,1),K_max_L_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_State_z(:,1),K_max_R_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_State_z(:,1),K_250_L_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_State_z(:,1),K_250_R_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_State_z(:,1),K_10_L_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_State_z(:,1),K_10_R_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_State_z(:,1),K_transfer_L_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_State_z(:,1),K_transfer_R_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_State_z(:,1),K_worksite_L_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
```

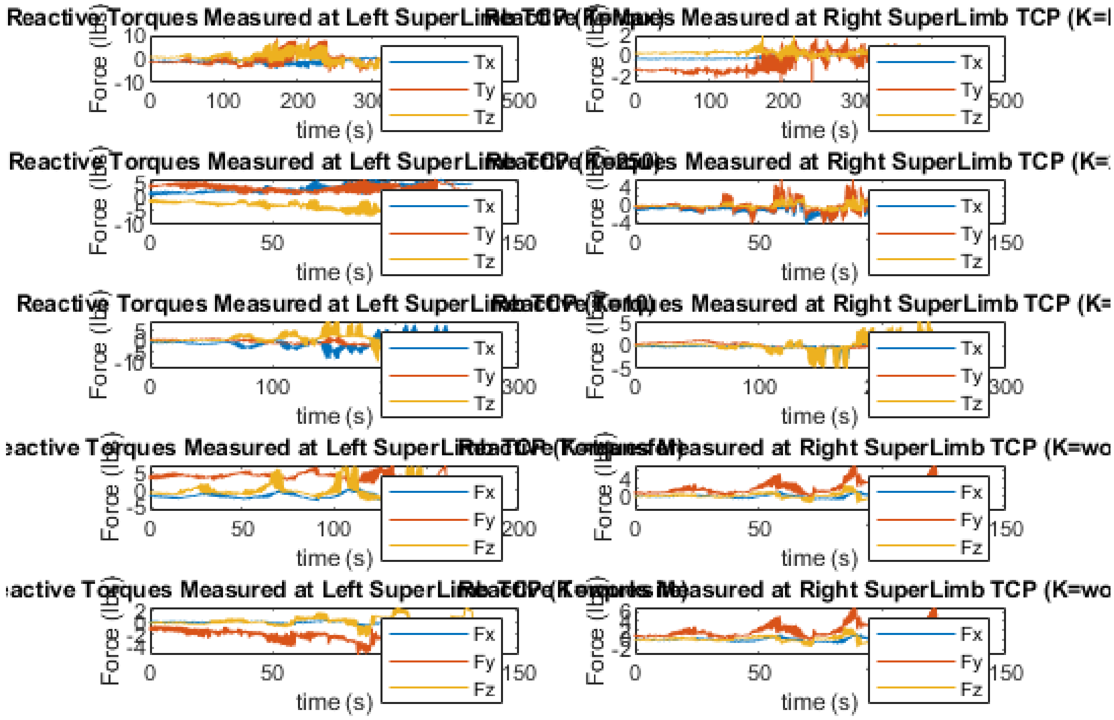
```
title('Joint State of Left SuperLimb (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_State_z(:,1),K_worksite_R_Jt_State_z(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=worksite)');
```


Operator Load applied to MANTIS (K=Max)
Operator Load applied to MANTIS (K=250)
Operator Load applied to MANTIS (K=10)
Operator Load applied to MANTIS (K=transfer)
Operator Load applied to MANTIS (K=worksite)
Operator Load (lbs)
time (s)

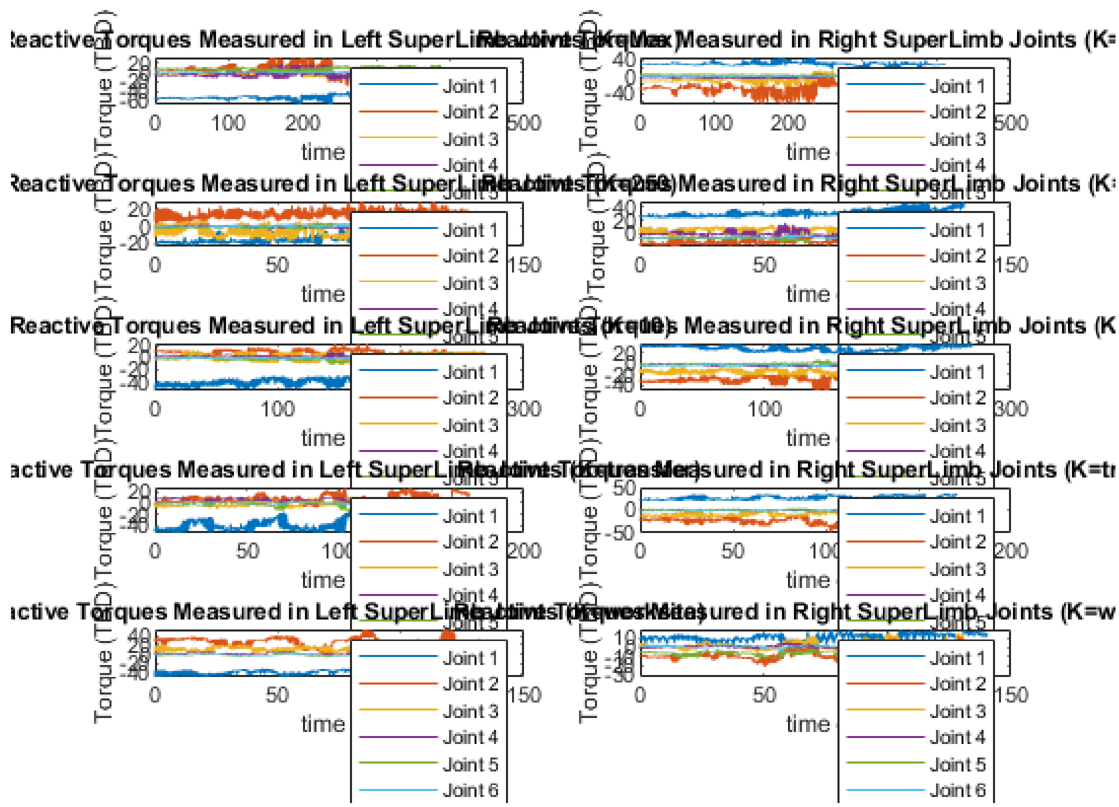

Astronaut Orientation (K=Max)
Astronaut Orientation (K=250)
Astronaut Orientation (K=10)
Astronaut Orientation (K=transfer)
Astronaut Orientation (K=worksite)
Angle (deg)
time (s)
Roll
Pitch
yaw
Yaw


Reactive Load Measured at Right Handrail (K=Max)
Reactive Load Measured at Right Handrail (K=250)
Reactive Load Measured at Right Handrail (K=10)
Reactive Load (lbs)
LC 1
LC 2
LC 3
LC 4
me (s)

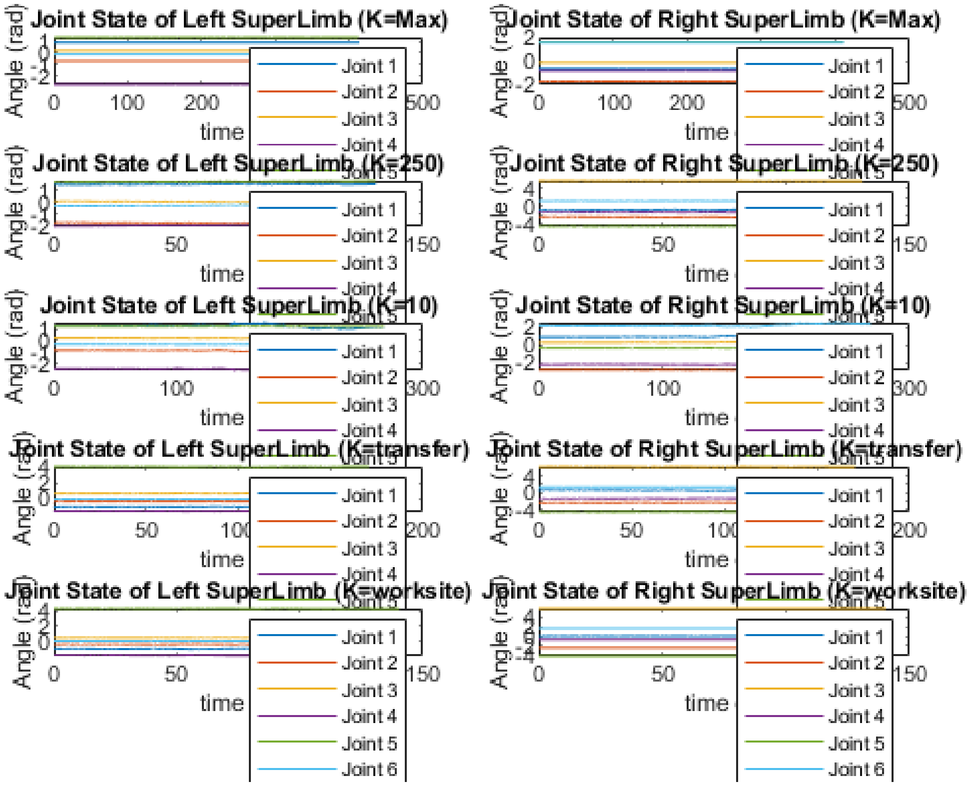

Reactive Forces Measured at Left SuperLimb TCP
Reactive Forces Measured at Right SuperLimb TCP
Force (lbs)
time (s)
Fx
Fy
Fz



Force (lb)
time (s)
Tx
Ty
Tz
Fx
Fy
Fz



Torque (TBD)
time
Joint 1
Joint 2
Joint 3
Joint 4
Joint 5
Joint 6



XX DIRECTION OPERATOR APPLIED TORQUE

```
%%PROCESSING OF IMU AND OPERATION LOAD CELL DATA%%
K_max_IMU_LC_xx = readmatrix("K_max_pose_2\IMU_LC_Data\test_xx_1_1.csv");
K_250_IMU_LC_xx = readmatrix("K_250_pose_4\IMU_LC_Data\test_xx_3_1.csv");
K_10_IMU_LC_xx = readmatrix("K_10_pose_3\IMU_LC_Data\test_xx_2_1.csv");
K_transfer_IMU_LC_xx = readmatrix("K_Transfer\IMU_LC_Data\Test_xx.csv");
K_worksite_IMU_LC_xx = readmatrix("K_Worksite\IMU_LC_Data\Test_xx.csv");

K_max_IMU_xx = [K_max_IMU_LC_xx(:,3:6)];
K_250_IMU_xx = [K_250_IMU_LC_xx(:,3:6)];
K_10_IMU_xx = [K_10_IMU_LC_xx(:,3:6)];
K_transfer_IMU_xx = [K_transfer_IMU_LC_xx(:,3:6)];
K_worksite_IMU_xx = [K_worksite_IMU_LC_xx(:,3:6)];

K_max_LC_xx = K_max_IMU_LC_xx(:,2:3);
K_250_LC_xx = K_250_IMU_LC_xx(:,2:3);
K_10_LC_xx = K_10_IMU_LC_xx(:,2:3);
K_transfer_LC_xx = K_transfer_IMU_LC_xx(:,2:3);
K_worksite_LC_xx = K_worksite_IMU_LC_xx(:,2:3);

%%PLOT xx OPERATOR LOAD CELL DATA%%
figure(1)
subplot(5,1,1)
plot(K_max_LC_xx(:,1),K_max_LC_xx(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=Max)');
subplot(5,1,2)
plot(K_250_LC_xx(:,1),K_250_LC_xx(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=250)');
subplot(5,1,3)
plot(K_10_LC_xx(:,1),K_10_LC_xx(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
```

```
title('Operator Load applied to MANTIS (K=10)');
subplot(5,1,4)
plot(K_transfer_LC_xx(:,1),K_transfer_LC_xx(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=transfer)');
subplot(5,1,5)
plot(K_worksite_LC_xx(:,1),K_worksite_LC_xx(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=worksite)');

%%PLOT IMU DATA%%
figure(2)
subplot(5,1,1)
plot(K_max_IMU_xx(:,1),K_max_IMU_xx(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=Max)');
subplot(5,1,2)
plot(K_250_IMU_xx(:,1),K_250_IMU_xx(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=250)');
subplot(5,1,3)
plot(K_10_IMU_xx(:,1),K_10_IMU_xx(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=10)');
subplot(5,1,4)
plot(K_transfer_IMU_xx(:,1),K_transfer_IMU_xx(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=transfer)');
subplot(5,1,5)
plot(K_worksite_IMU_xx(:,1),K_worksite_IMU_xx(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=worksite)');

%%PROCESSING OF HANDRAIL DATA%%
K_max_R_HR_xx = readmatrix("K_max_pose_2\Handrail_Data\test_xx_1_1_black.csv");
K_max_L_HR_xx = readmatrix("K_max_pose_2\Handrail_Data\test_xx_1_1_white.csv");
K_250_R_HR_xx = readmatrix("K_250_pose_4\Handrail_Data\test_xx_3_1_black.csv");
K_250_L_HR_xx = readmatrix("K_250_pose_4\Handrail_Data\test_xx_3_1_white.csv");
K_10_R_HR_xx = readmatrix("K_10_pose_3\Handrail_Data\test_xx_2_1_black.csv");
K_10_L_HR_xx = readmatrix("K_10_pose_3\Handrail_Data\test_xx_2_1_white.csv");
K_transfer_R_HR_xx = readmatrix("K_Transfer\Handrail_Data\test_xx_black.csv");
K_transfer_L_HR_xx = readmatrix("K_Transfer\Handrail_Data\test_xx_white.csv");
K_worksite_R_HR_xx = readmatrix("K_Worksite\Handrail_Data\test_xx_black.csv");
K_worksite_L_HR_xx = readmatrix("K_Worksite\Handrail_Data\test_xx_white.csv");

%%PLOT HANDRAIL DATA%%
figure(3)
subplot(5,2,1)
plot(K_max_L_HR_xx(:,1),K_max_L_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=Max)');
subplot(5,2,2)
plot(K_max_R_HR_xx(:,1),K_max_R_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=Max)');
```

```
subplot(5,2,3)
plot(K_250_L_HR_xx(:,1),K_250_L_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=250)');
subplot(5,2,4)
plot(K_250_R_HR_xx(:,1),K_250_R_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=250)');
subplot(5,2,5)
plot(K_10_L_HR_xx(:,1),K_10_L_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=10)');
subplot(5,2,6)
plot(K_10_R_HR_xx(:,1),K_10_R_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=10)');
subplot(5,2,7)
plot(K_transfer_L_HR_xx(:,1),K_transfer_L_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_HR_xx(:,1),K_transfer_R_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_HR_xx(:,1),K_worksite_L_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_HR_xx(:,1),K_worksite_R_HR_xx(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=worksite)');

%%PROCESSING OF UR5E DATA%%
K_max_R_FT_xx = readmatrix("K_max_pose_2\UR5e_Data\test_xx_1_1\right_ft_data_modified.csv");
K_max_L_FT_xx = readmatrix("K_max_pose_2\UR5e_Data\test_xx_1_1\left_ft_data_modified.csv");
K_250_R_FT_xx = readmatrix("K_250_pose_4\UR5e_Data\test_xx_3_1\right_ft_data.csv");
K_250_L_FT_xx = readmatrix("K_250_pose_4\UR5e_Data\test_xx_3_1\left_ft_data.csv");
K_10_R_FT_xx = readmatrix("K_10_pose_3\UR5e_Data\test_xx_2_1\right_ft_data.csv");
K_10_L_FT_xx = readmatrix("K_10_pose_3\UR5e_Data\test_xx_2_1\left_ft_data.csv");
K_transfer_R_FT_xx = readmatrix("K_Transfer\UR5e_Data\K_Transfer_XX\right_ft_data.csv");
K_transfer_L_FT_xx = readmatrix("K_Transfer\UR5e_Data\K_Transfer_XX\left_ft_data.csv");
K_worksite_R_FT_xx = readmatrix("K_Worksite\UR5e_Data\K_Worksite_XX\right_ft_data.csv");
K_worksite_L_FT_xx = readmatrix("K_Worksite\UR5e_Data\K_Worksite_XX\left_ft_data.csv");

K_max_R_FT_xx = [K_max_R_FT_xx(:,3),K_max_R_FT_xx(:,5:10)];
K_max_L_FT_xx = [K_max_L_FT_xx(:,3),K_max_L_FT_xx(:,5:10)];
K_250_R_FT_xx = [K_250_R_FT_xx(:,3),K_250_R_FT_xx(:,5:10)];
K_250_L_FT_xx = [K_250_L_FT_xx(:,3),K_250_L_FT_xx(:,5:10)];
K_10_R_FT_xx = [K_10_R_FT_xx(:,3),K_10_R_FT_xx(:,5:10)];
K_10_L_FT_xx = [K_10_L_FT_xx(:,3),K_10_L_FT_xx(:,5:10)];
K_transfer_R_FT_xx = [K_transfer_R_FT_xx(:,3),K_transfer_R_FT_xx(:,5:10)];
K_transfer_L_FT_xx = [K_transfer_L_FT_xx(:,3),K_transfer_L_FT_xx(:,5:10)];
K_worksite_R_FT_xx = [K_worksite_R_FT_xx(:,3),K_worksite_R_FT_xx(:,5:10)];
```

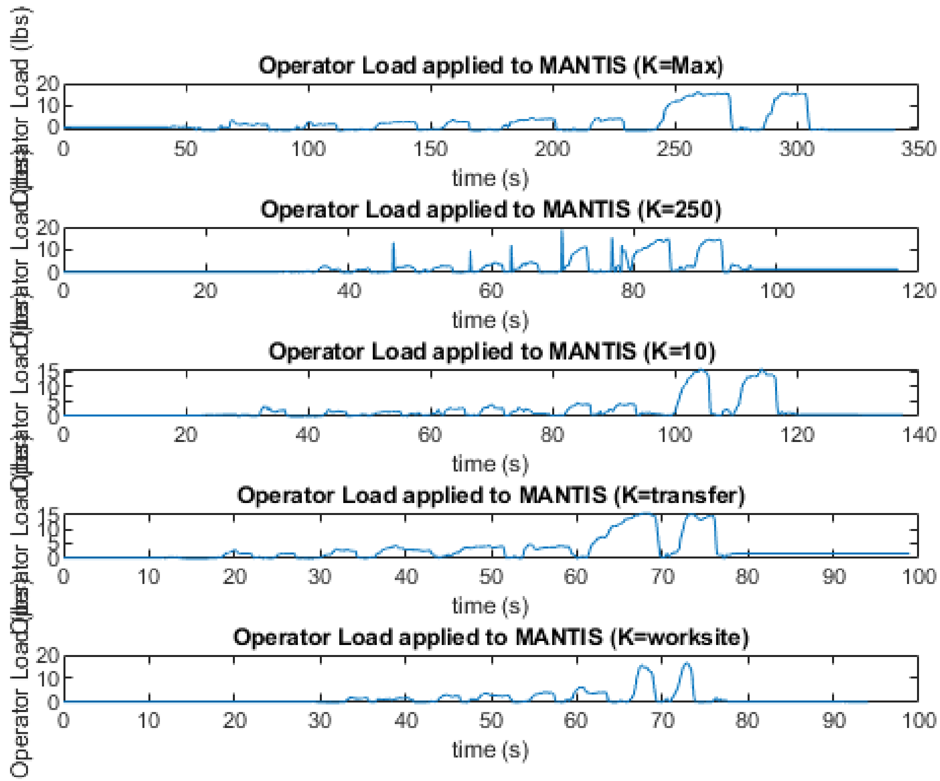
```
K_worksite_L_FT_xx = [K_worksite_L_FT_xx(:,3),K_worksite_L_FT_xx(:,5:10)];

K_max_R_Jt_Trq_xx = readmatrix("K_max_pose_2\UR5e_Data\test_xx_1_1\right_joint_torques.csv");
K_max_L_Jt_Trq_xx = readmatrix("K_max_pose_2\UR5e_Data\test_xx_1_1\left_joint_torques.csv");
K_250_R_Jt_Trq_xx = readmatrix("K_250_pose_4\UR5e_Data\test_xx_3_1\right_joint_torques.csv");
K_250_L_Jt_Trq_xx = readmatrix("K_250_pose_4\UR5e_Data\test_xx_3_1\left_joint_torques.csv");
K_10_R_Jt_Trq_xx = readmatrix("K_10_pose_3\UR5e_Data\test_xx_2_1\right_joint_torques.csv");
K_10_L_Jt_Trq_xx = readmatrix("K_10_pose_3\UR5e_Data\test_xx_2_1\left_joint_torques.csv");
K_transfer_R_Jt_Trq_xx = readmatrix("K_Transfer\UR5e_Data\K_Transfer_XX\right_joint_torques.csv");
K_transfer_L_Jt_Trq_xx = readmatrix("K_Transfer\UR5e_Data\K_Transfer_XX\left_joint_torques.csv");
K_worksite_R_Jt_Trq_xx = readmatrix("K_Worksite\UR5e_Data\K_Worksite_XX\right_joint_torques.csv");
K_worksite_L_Jt_Trq_xx = readmatrix("K_Worksite\UR5e_Data\K_Worksite_XX\left_joint_torques.csv");

K_max_R_Jt_Trq_xx = K_max_R_Jt_Trq_xx(:,2:8);
K_max_L_Jt_Trq_xx = K_max_L_Jt_Trq_xx(:,2:8);
K_250_R_Jt_Trq_xx = K_250_R_Jt_Trq_xx(:,2:8);
K_250_L_Jt_Trq_xx = K_250_L_Jt_Trq_xx(:,2:8);
K_10_R_Jt_Trq_xx = K_10_R_Jt_Trq_xx(:,2:8);
K_10_L_Jt_Trq_xx = K_10_L_Jt_Trq_xx(:,2:8);
K_transfer_R_Jt_Trq_xx = K_transfer_R_Jt_Trq_xx(:,2:8);
K_transfer_L_Jt_Trq_xx = K_transfer_L_Jt_Trq_xx(:,2:8);
K_worksite_R_Jt_Trq_xx = K_worksite_R_Jt_Trq_xx(:,2:8);
K_worksite_L_Jt_Trq_xx = K_worksite_L_Jt_Trq_xx(:,2:8);

K_max_R_Jt_State_xx = readmatrix("K_max_pose_2\UR5e_Data\test_xx_1_1\right_joint_states.csv");
K_max_L_Jt_State_xx = readmatrix("K_max_pose_2\UR5e_Data\test_xx_1_1\left_joint_states.csv");
K_250_R_Jt_State_xx = readmatrix("K_250_pose_4\UR5e_Data\test_xx_3_1\right_joint_states.csv");
K_250_L_Jt_State_xx = readmatrix("K_250_pose_4\UR5e_Data\test_xx_3_1\left_joint_states.csv");
K_10_R_Jt_State_xx = readmatrix("K_10_pose_3\UR5e_Data\test_xx_2_1\right_joint_states.csv");
K_10_L_Jt_State_xx = readmatrix("K_10_pose_3\UR5e_Data\test_xx_2_1\left_joint_states.csv");
K_transfer_R_Jt_State_xx = readmatrix("K_Transfer\UR5e_Data\K_Transfer_XX\right_joint_states.csv");
K_transfer_L_Jt_State_xx = readmatrix("K_Transfer\UR5e_Data\K_Transfer_XX\left_joint_states.csv");
K_worksite_R_Jt_State_xx = readmatrix("K_Worksite\UR5e_Data\K_Worksite_XX\right_joint_states.csv");
K_worksite_L_Jt_State_xx = readmatrix("K_Worksite\UR5e_Data\K_Worksite_XX\left_joint_states.csv");

K_max_R_Jt_State_xx = [K_max_R_Jt_State_xx(:,3),K_max_R_Jt_State_xx(:,10:15)];
K_max_L_Jt_State_xx = [K_max_L_Jt_State_xx(:,3),K_max_L_Jt_State_xx(:,10:15)];
K_250_R_Jt_State_xx = [K_250_R_Jt_State_xx(:,3),K_250_R_Jt_State_xx(:,10:15)];
K_250_L_Jt_State_xx = [K_250_L_Jt_State_xx(:,3),K_250_L_Jt_State_xx(:,10:15)];
K_10_R_Jt_State_xx = [K_10_R_Jt_State_xx(:,3),K_10_R_Jt_State_xx(:,10:15)];
K_10_L_Jt_State_xx = [K_10_L_Jt_State_xx(:,3),K_10_L_Jt_State_xx(:,10:15)];
K_transfer_R_Jt_State_xx = [K_transfer_R_Jt_State_xx(:,3),K_transfer_R_Jt_State_xx(:,10:15)];
K_transfer_L_Jt_State_xx = [K_transfer_L_Jt_State_xx(:,3),K_transfer_L_Jt_State_xx(:,10:15)];
K_worksite_R_Jt_State_xx = [K_worksite_R_Jt_State_xx(:,3),K_worksite_R_Jt_State_xx(:,10:15)];
K_worksite_L_Jt_State_xx = [K_worksite_L_Jt_State_xx(:,3),K_worksite_L_Jt_State_xx(:,10:15)];

%%PLOT UR5E DATA%%
figure(4)
subplot(5,2,1)
plot(K_max_L_FT_xx(:,1),K_max_L_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_xx(:,1),K_max_R_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_xx(:,1),K_250_L_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
```

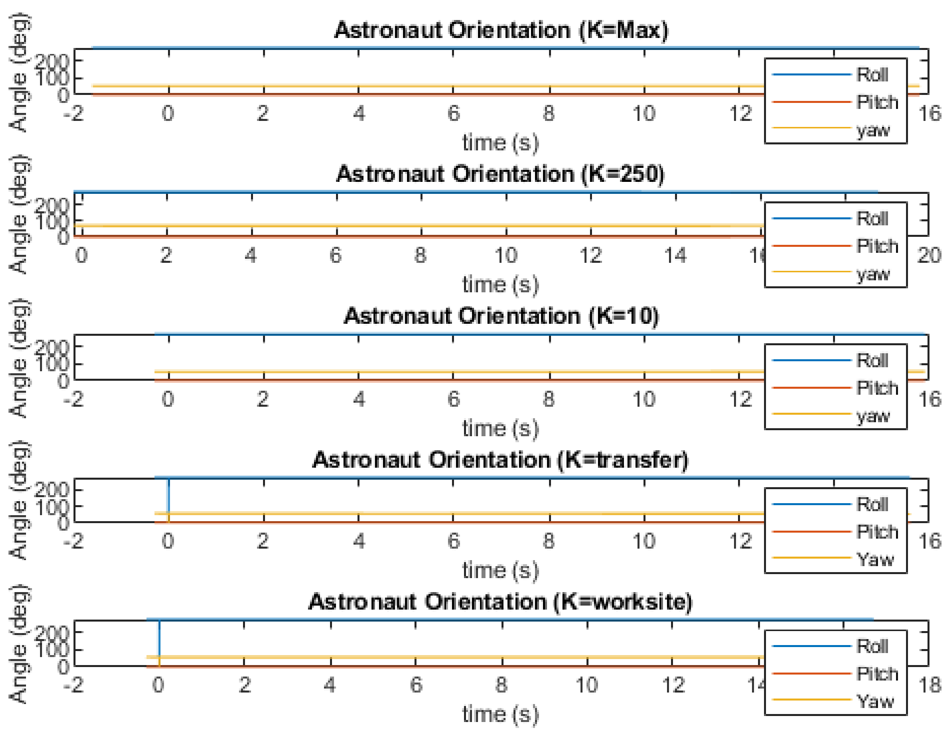
```
title('Reactive Forces Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_xx(:,1),K_250_R_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_xx(:,1),K_10_L_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_xx(:,1),K_10_R_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_xx(:,1),K_transfer_L_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_FT_xx(:,1),K_transfer_R_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_FT_xx(:,1),K_worksite_L_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_xx(:,1),K_worksite_R_FT_xx(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=worksite)');

figure(5)
subplot(5,2,1)
plot(K_max_L_FT_xx(:,1),K_max_L_FT_xx(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_xx(:,1),K_max_R_FT_xx(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_xx(:,1),K_250_L_FT_xx(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_xx(:,1),K_250_R_FT_xx(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_xx(:,1),K_10_L_FT_xx(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
```

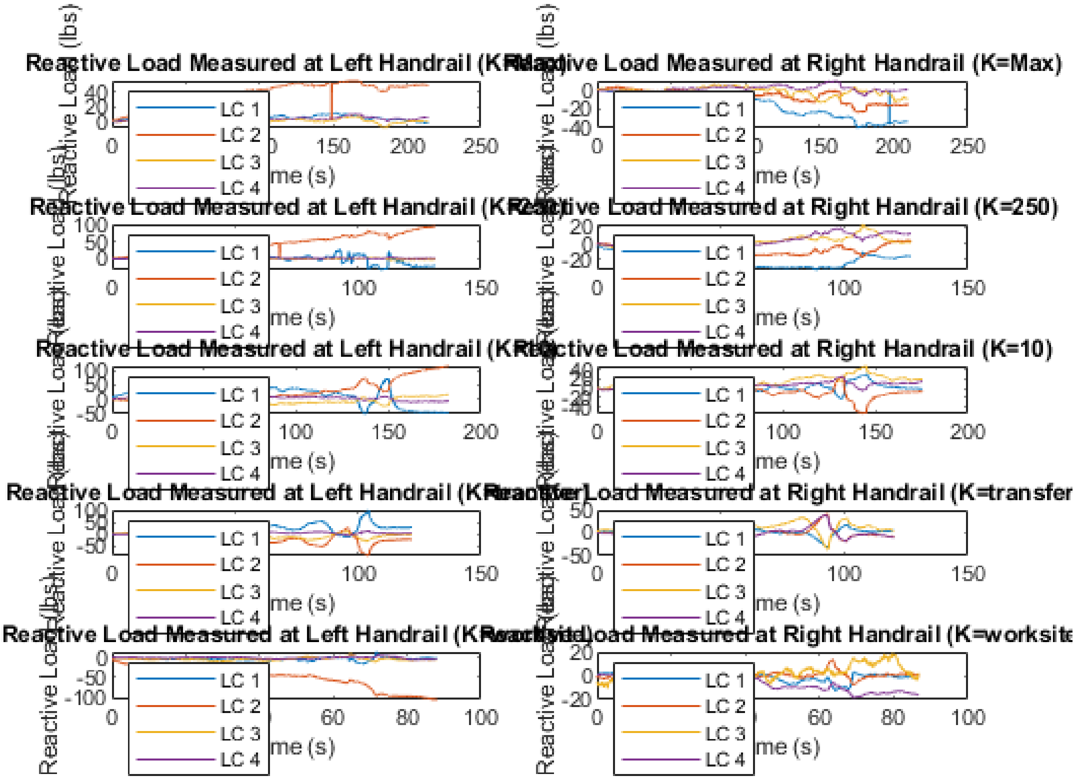
```
title('Reactive Torques Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_xx(:,1),K_10_R_FT_xx(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_xx(:,1),K_transfer_L_FT_xx(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_worksite_R_FT_xx(:,1),K_worksite_R_FT_xx(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');
subplot(5,2,9)
plot(K_worksite_L_FT_xx(:,1),K_worksite_L_FT_xx(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_xx(:,1),K_worksite_R_FT_xx(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');

figure(6)
subplot(5,2,1)
plot(K_max_L_Jt_Trq_xx(:,1),K_max_L_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_Trq_xx(:,1),K_max_R_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_Trq_xx(:,1),K_250_L_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_Trq_xx(:,1),K_250_R_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_Trq_xx(:,1),K_10_L_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_Trq_xx(:,1),K_10_R_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_Trq_xx(:,1),K_transfer_L_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
```

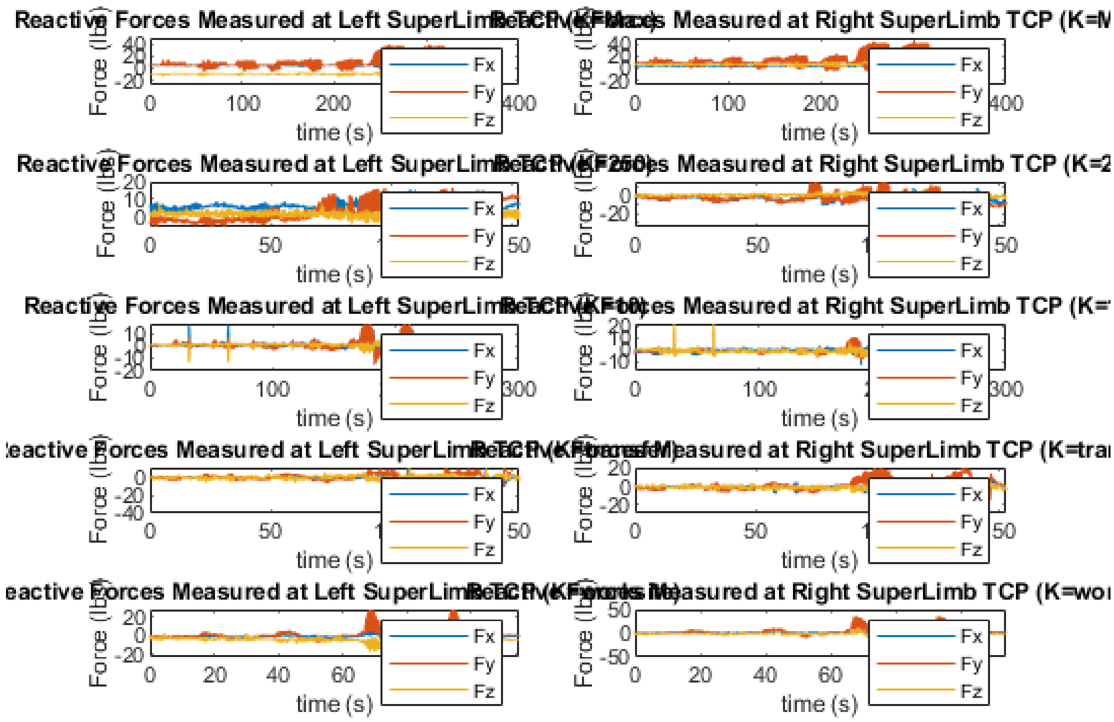
```
title('Reactive Torques Measured in Left SuperLimb Joints (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_Trq_xx(:,1),K_transfer_R_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_Trq_xx(:,1),K_worksite_L_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_Trq_xx(:,1),K_worksite_R_Jt_Trq_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=worksite)');

figure(7)
subplot(5,2,1)
plot(K_max_L_Jt_State_xx(:,1),K_max_L_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_State_xx(:,1),K_max_R_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_State_xx(:,1),K_250_L_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_State_xx(:,1),K_250_R_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_State_xx(:,1),K_10_L_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_State_xx(:,1),K_10_R_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_State_xx(:,1),K_transfer_L_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_State_xx(:,1),K_transfer_R_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_State_xx(:,1),K_worksite_L_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
```

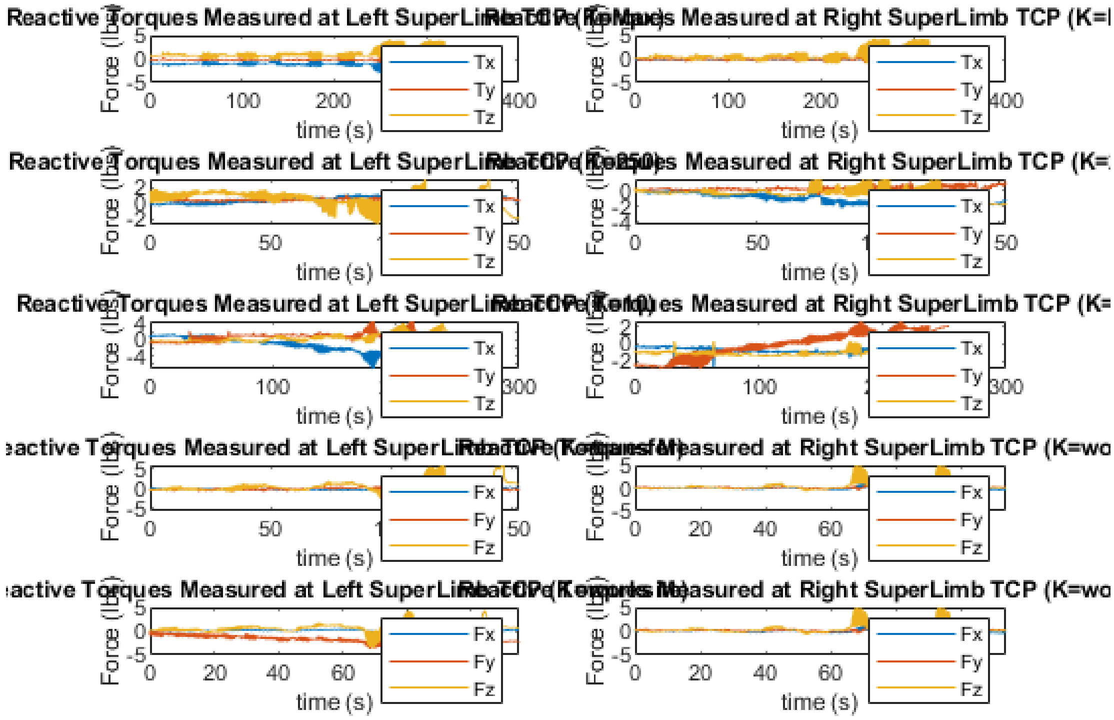
```
title('Joint State of Left SuperLimb (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_State_xx(:,1),K_worksite_R_Jt_State_xx(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=worksite)');
```

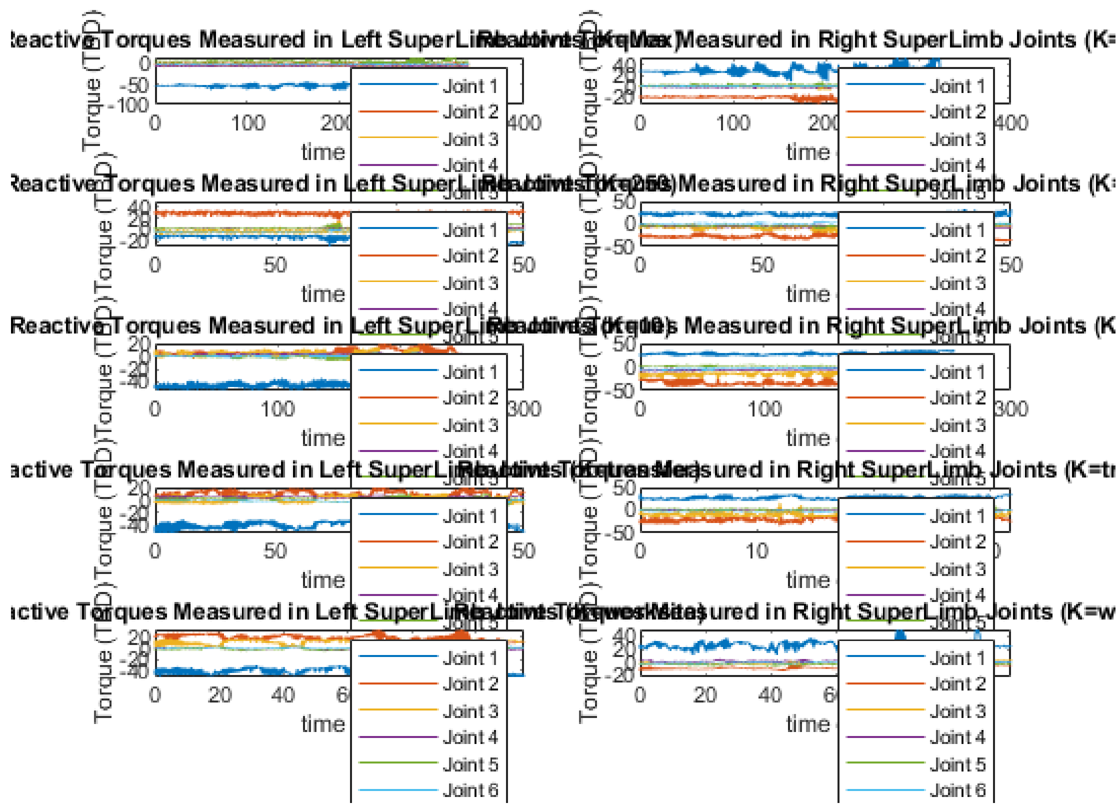

Operator Load applied to MANTIS (K=Max)
Operator Load applied to MANTIS (K=250)
Operator Load applied to MANTIS (K=10)
Operator Load applied to MANTIS (K=transfer)
Operator Load applied to MANTIS (K=worksite)
Operator Load (lbs)
time (s)

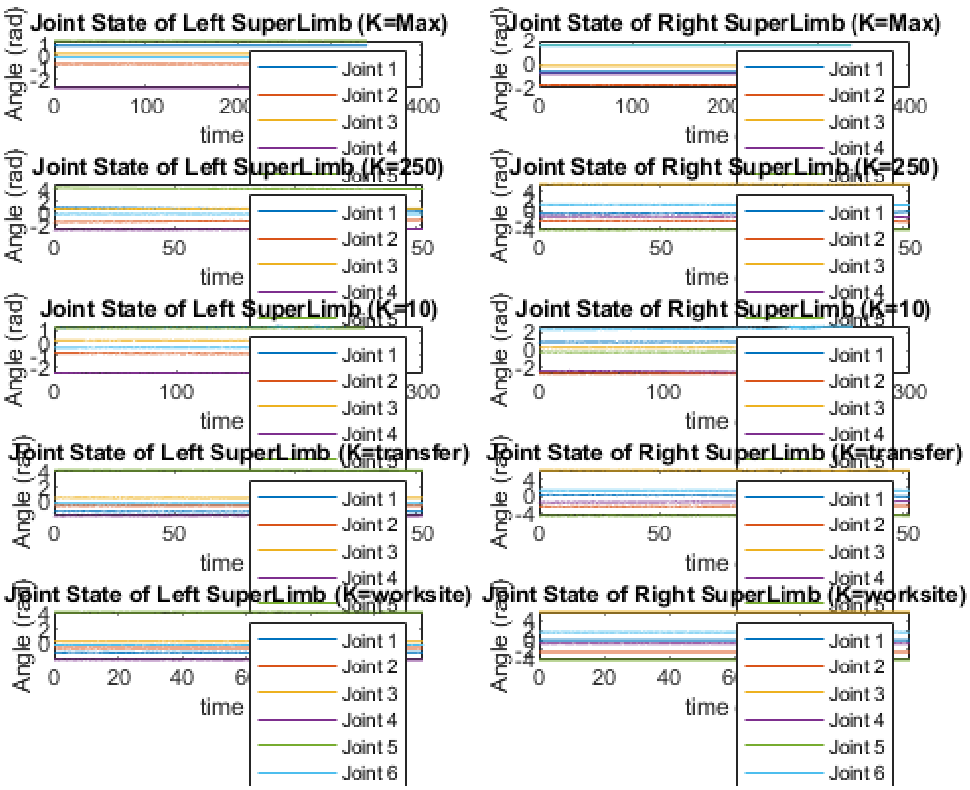

Astronaut Orientation (K=Max)
Astronaut Orientation (K=250)
Astronaut Orientation (K=10)
Astronaut Orientation (K=transfer)
Astronaut Orientation (K=worksite)
Angle (deg)
time (s)
Roll
Pitch
yaw
Yaw


Reactive Load Measured at Right Handrail (K=Max)
Reactive Load Measured at Right Handrail (K=250)
Reactive Load Measured at Right Handrail (K=10)
LC 1
LC 2
LC 3
LC 4
Reactive Load (lbs)


Fx
Fy
Fz
Force (lbs)
time (s)


Measured at Right SuperLimb TCP
Force (lb)
time (s)
Tx
Ty
Tz
Fx
Fy
Fz


Measured in Right SuperLimb Joints
Torque
time
Joint 1
Joint 2
Joint 3
Joint 4
Joint 5
Joint 6



YY DIRECTION OPERATOR APPLIED TORQUE %%

```
%%PROCESSING OF IMU AND OPERATION LOAD CELL DATA%%
K_max_IMU_LC_yy = readmatrix("K_max_pose_2\IMU_LC_Data\test_yy_1_1.csv");
K_250_IMU_LC_yy = readmatrix("K_250_pose_4\IMU_LC_Data\test_yy_3_1.csv");
K_10_IMU_LC_yy = readmatrix("K_10_pose_3\IMU_LC_Data\test_yy_2_1.csv");
K_transfer_IMU_LC_yy = readmatrix("K_Transfer\IMU_LC_Data\Test_yy.csv");
K_worksite_IMU_LC_yy = readmatrix("K_Worksite\IMU_LC_Data\Test_yy.csv");

K_max_IMU_yy = [K_max_IMU_LC_yy(:,3:6)];
K_250_IMU_yy = [K_250_IMU_LC_yy(:,3:6)];
K_10_IMU_yy = [K_10_IMU_LC_yy(:,3:6)];
K_transfer_IMU_yy = [K_transfer_IMU_LC_yy(:,3:6)];
K_worksite_IMU_yy = [K_worksite_IMU_LC_yy(:,3:6)];

K_max_LC_yy = K_max_IMU_LC_yy(:,2:3);
K_250_LC_yy = K_250_IMU_LC_yy(:,2:3);
K_10_LC_yy = K_10_IMU_LC_yy(:,2:3);
K_transfer_LC_yy = K_transfer_IMU_LC_yy(:,2:3);
K_worksite_LC_yy = K_worksite_IMU_LC_yy(:,2:3);

%%PLOT yy OPERATOR LOAD CELL DATA%%
figure(1)
subplot(5,1,1)
plot(K_max_LC_yy(:,1),K_max_LC_yy(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=Max)');
subplot(5,1,2)
plot(K_250_LC_yy(:,1),K_250_LC_yy(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=250)');
subplot(5,1,3)
plot(K_10_LC_yy(:,1),K_10_LC_yy(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
```

```
title('Operator Load applied to MANTIS (K=10)');
subplot(5,1,4)
plot(K_transfer_LC_yy(:,1),K_transfer_LC_yy(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=transfer)');
subplot(5,1,5)
plot(K_worksite_LC_yy(:,1),K_worksite_LC_yy(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=worksite)');

%%PLOT IMU DATA%%
figure(2)
subplot(5,1,1)
plot(K_max_IMU_yy(:,1),K_max_IMU_yy(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=Max)');
subplot(5,1,2)
plot(K_250_IMU_yy(:,1),K_250_IMU_yy(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=250)');
subplot(5,1,3)
plot(K_10_IMU_yy(:,1),K_10_IMU_yy(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=10)');
subplot(5,1,4)
plot(K_transfer_IMU_yy(:,1),K_transfer_IMU_yy(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=transfer)');
subplot(5,1,5)
plot(K_worksite_IMU_yy(:,1),K_worksite_IMU_yy(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=worksite)');

%%PROCESSING OF HANDRAIL DATA%%
K_max_R_HR_yy = readmatrix("K_max_pose_2\Handrail_Data\test_yy_1_1_black.csv");
K_max_L_HR_yy = readmatrix("K_max_pose_2\Handrail_Data\test_yy_1_1_white.csv");
K_250_R_HR_yy = readmatrix("K_250_pose_4\Handrail_Data\test_yy_3_1_black.csv");
K_250_L_HR_yy = readmatrix("K_250_pose_4\Handrail_Data\test_yy_3_1_white.csv");
K_10_R_HR_yy = readmatrix("K_10_pose_3\Handrail_Data\test_yy_2_1_black.csv");
K_10_L_HR_yy = readmatrix("K_10_pose_3\Handrail_Data\test_yy_2_1_white.csv");
K_transfer_R_HR_yy = readmatrix("K_Transfer\Handrail_Data\test_yy_black.csv");
K_transfer_L_HR_yy = readmatrix("K_Transfer\Handrail_Data\test_yy_white.csv");
K_worksite_R_HR_yy = readmatrix("K_Worksite\Handrail_Data\test_yy_black.csv");
K_worksite_L_HR_yy = readmatrix("K_Worksite\Handrail_Data\test_yy_white.csv");

%%PLOT HANDRAIL DATA%%
figure(3)
subplot(5,2,1)
plot(K_max_L_HR_yy(:,1),K_max_L_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=Max)');
subplot(5,2,2)
plot(K_max_R_HR_yy(:,1),K_max_R_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=Max)');
```

```
subplot(5,2,3)
plot(K_250_L_HR_yy(:,1),K_250_L_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=250)');
subplot(5,2,4)
plot(K_250_R_HR_yy(:,1),K_250_R_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=250)');
subplot(5,2,5)
plot(K_10_L_HR_yy(:,1),K_10_L_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=10)');
subplot(5,2,6)
plot(K_10_R_HR_yy(:,1),K_10_R_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=10)');
subplot(5,2,7)
plot(K_transfer_L_HR_yy(:,1),K_transfer_L_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_HR_yy(:,1),K_transfer_R_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_HR_yy(:,1),K_worksite_L_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_HR_yy(:,1),K_worksite_R_HR_yy(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=worksite)');

%%PROCESSING OF UR5E DATA%%
K_max_R_FT_yy = readmatrix("K_max_pose_2\UR5e_Data\test_yy_1_1\right_ft_data.csv");
K_max_L_FT_yy = readmatrix("K_max_pose_2\UR5e_Data\test_yy_1_1\left_ft_data.csv");
K_250_R_FT_yy = readmatrix("K_250_pose_4\UR5e_Data\test_yy_3_1\right_ft_data.csv");
K_250_L_FT_yy = readmatrix("K_250_pose_4\UR5e_Data\test_yy_3_1\left_ft_data.csv");
K_10_R_FT_yy = readmatrix("K_10_pose_3\UR5e_Data\test_yy_2_1\right_ft_data.csv");
K_10_L_FT_yy = readmatrix("K_10_pose_3\UR5e_Data\test_yy_2_1\left_ft_data.csv");
K_transfer_R_FT_yy = readmatrix("K_Transfer\UR5e_Data\K_Transfer_YY\right_ft_data.csv");
K_transfer_L_FT_yy = readmatrix("K_Transfer\UR5e_Data\K_Transfer_YY\left_ft_data.csv");
K_worksite_R_FT_yy = readmatrix("K_Worksite\UR5e_Data\K_Worksite_YY\right_ft_data.csv");
K_worksite_L_FT_yy = readmatrix("K_Worksite\UR5e_Data\K_Worksite_YY\left_ft_data.csv");

K_max_R_FT_yy = [K_max_R_FT_yy(:,3),K_max_R_FT_yy(:,5:10)];
K_max_L_FT_yy = [K_max_L_FT_yy(:,3),K_max_L_FT_yy(:,5:10)];
K_250_R_FT_yy = [K_250_R_FT_yy(:,3),K_250_R_FT_yy(:,5:10)];
K_250_L_FT_yy = [K_250_L_FT_yy(:,3),K_250_L_FT_yy(:,5:10)];
K_10_R_FT_yy = [K_10_R_FT_yy(:,3),K_10_R_FT_yy(:,5:10)];
K_10_L_FT_yy = [K_10_L_FT_yy(:,3),K_10_L_FT_yy(:,5:10)];
K_transfer_R_FT_yy = [K_transfer_R_FT_yy(:,3),K_transfer_R_FT_yy(:,5:10)];
K_transfer_L_FT_yy = [K_transfer_L_FT_yy(:,3),K_transfer_L_FT_yy(:,5:10)];
K_worksite_R_FT_yy = [K_worksite_R_FT_yy(:,3),K_worksite_R_FT_yy(:,5:10)];
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```
K_worksite_L_FT_yy = [K_worksite_L_FT_yy(:,3),K_worksite_L_FT_yy(:,5:10)];

K_max_R_Jt_Trq_yy = readmatrix("K_max_pose_2\UR5e_Data\test_yy_1_1\right_joint_torques.csv");
K_max_L_Jt_Trq_yy = readmatrix("K_max_pose_2\UR5e_Data\test_yy_1_1\left_joint_torques.csv");
K_250_R_Jt_Trq_yy = readmatrix("K_250_pose_4\UR5e_Data\test_yy_3_1\right_joint_torques.csv");
K_250_L_Jt_Trq_yy = readmatrix("K_250_pose_4\UR5e_Data\test_yy_3_1\left_joint_torques.csv");
K_10_R_Jt_Trq_yy = readmatrix("K_10_pose_3\UR5e_Data\test_yy_2_1\right_joint_torques.csv");
K_10_L_Jt_Trq_yy = readmatrix("K_10_pose_3\UR5e_Data\test_yy_2_1\left_joint_torques.csv");
K_transfer_R_Jt_Trq_yy = readmatrix("K_Transfer\UR5e_Data\K_Transfer_YY\right_joint_torques.csv");
K_transfer_L_Jt_Trq_yy = readmatrix("K_Transfer\UR5e_Data\K_Transfer_YY\left_joint_torques.csv");
K_worksite_R_Jt_Trq_yy = readmatrix("K_Worksite\UR5e_Data\K_Worksite_YY\right_joint_torques.csv");
K_worksite_L_Jt_Trq_yy = readmatrix("K_Worksite\UR5e_Data\K_Worksite_YY\left_joint_torques.csv");

K_max_R_Jt_Trq_yy = K_max_R_Jt_Trq_yy(:,2:8);
K_max_L_Jt_Trq_yy = K_max_L_Jt_Trq_yy(:,2:8);
K_250_R_Jt_Trq_yy = K_250_R_Jt_Trq_yy(:,2:8);
K_250_L_Jt_Trq_yy = K_250_L_Jt_Trq_yy(:,2:8);
K_10_R_Jt_Trq_yy = K_10_R_Jt_Trq_yy(:,2:8);
K_10_L_Jt_Trq_yy = K_10_L_Jt_Trq_yy(:,2:8);
K_transfer_R_Jt_Trq_yy = K_transfer_R_Jt_Trq_yy(:,2:8);
K_transfer_L_Jt_Trq_yy = K_transfer_L_Jt_Trq_yy(:,2:8);
K_worksite_R_Jt_Trq_yy = K_worksite_R_Jt_Trq_yy(:,2:8);
K_worksite_L_Jt_Trq_yy = K_worksite_L_Jt_Trq_yy(:,2:8);

K_max_R_Jt_State_yy = readmatrix("K_max_pose_2\UR5e_Data\test_yy_1_1\right_joint_states.csv");
K_max_L_Jt_State_yy = readmatrix("K_max_pose_2\UR5e_Data\test_yy_1_1\left_joint_states.csv");
K_250_R_Jt_State_yy = readmatrix("K_250_pose_4\UR5e_Data\test_yy_3_1\right_joint_states.csv");
K_250_L_Jt_State_yy = readmatrix("K_250_pose_4\UR5e_Data\test_yy_3_1\left_joint_states.csv");
K_10_R_Jt_State_yy = readmatrix("K_10_pose_3\UR5e_Data\test_yy_2_1\right_joint_states.csv");
K_10_L_Jt_State_yy = readmatrix("K_10_pose_3\UR5e_Data\test_yy_2_1\left_joint_states.csv");
K_transfer_R_Jt_State_yy = readmatrix("K_Transfer\UR5e_Data\K_Transfer_YY\right_joint_states.csv");
K_transfer_L_Jt_State_yy = readmatrix("K_Transfer\UR5e_Data\K_Transfer_YY\left_joint_states.csv");
K_worksite_R_Jt_State_yy = readmatrix("K_Worksite\UR5e_Data\K_Worksite_YY\right_joint_states.csv");
K_worksite_L_Jt_State_yy = readmatrix("K_Worksite\UR5e_Data\K_Worksite_YY\left_joint_states.csv");

K_max_R_Jt_State_yy = [K_max_R_Jt_State_yy(:,3),K_max_R_Jt_State_yy(:,10:15)];
K_max_L_Jt_State_yy = [K_max_L_Jt_State_yy(:,3),K_max_L_Jt_State_yy(:,10:15)];
K_250_R_Jt_State_yy = [K_250_R_Jt_State_yy(:,3),K_250_R_Jt_State_yy(:,10:15)];
K_250_L_Jt_State_yy = [K_250_L_Jt_State_yy(:,3),K_250_L_Jt_State_yy(:,10:15)];
K_10_R_Jt_State_yy = [K_10_R_Jt_State_yy(:,3),K_10_R_Jt_State_yy(:,10:15)];
K_10_L_Jt_State_yy = [K_10_L_Jt_State_yy(:,3),K_10_L_Jt_State_yy(:,10:15)];
K_transfer_R_Jt_State_yy = [K_transfer_R_Jt_State_yy(:,3),K_transfer_R_Jt_State_yy(:,10:15)];
K_transfer_L_Jt_State_yy = [K_transfer_L_Jt_State_yy(:,3),K_transfer_L_Jt_State_yy(:,10:15)];
K_worksite_R_Jt_State_yy = [K_worksite_R_Jt_State_yy(:,3),K_worksite_R_Jt_State_yy(:,10:15)];
K_worksite_L_Jt_State_yy = [K_worksite_L_Jt_State_yy(:,3),K_worksite_L_Jt_State_yy(:,10:15)];

%%PLOT UR5E DATA%%
figure(4)
subplot(5,2,1)
plot(K_max_L_FT_yy(:,1),K_max_L_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_yy(:,1),K_max_R_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_yy(:,1),K_250_L_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
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```
title('Reactive Forces Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_yy(:,1),K_250_R_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_yy(:,1),K_10_L_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_yy(:,1),K_10_R_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_yy(:,1),K_transfer_L_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_FT_yy(:,1),K_transfer_R_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_FT_yy(:,1),K_worksite_L_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_yy(:,1),K_worksite_R_FT_yy(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=worksite)');


figure(5)
subplot(5,2,1)
plot(K_max_L_FT_yy(:,1),K_max_L_FT_yy(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_yy(:,1),K_max_R_FT_yy(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_yy(:,1),K_250_L_FT_yy(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_yy(:,1),K_250_R_FT_yy(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_yy(:,1),K_10_L_FT_yy(:,5:7));
legend('Tx','Ty','Tz'),
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xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_yy(:,1),K_10_R_FT_yy(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_yy(:,1),K_transfer_L_FT_yy(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_worksite_R_FT_yy(:,1),K_worksite_R_FT_yy(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');
subplot(5,2,9)
plot(K_worksite_L_FT_yy(:,1),K_worksite_L_FT_yy(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_yy(:,1),K_worksite_R_FT_yy(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');

figure(6)
subplot(5,2,1)
plot(K_max_L_Jt_Trq_yy(:,1),K_max_L_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_Trq_yy(:,1),K_max_R_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_Trq_yy(:,1),K_250_L_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_Trq_yy(:,1),K_250_R_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_Trq_yy(:,1),K_10_L_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_Trq_yy(:,1),K_10_R_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_Trq_yy(:,1),K_transfer_L_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
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xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_Trq_yy(:,1),K_transfer_R_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_Trq_yy(:,1),K_worksite_L_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_Trq_yy(:,1),K_worksite_R_Jt_Trq_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=worksite)');

figure(7)
subplot(5,2,1)
plot(K_max_L_Jt_State_yy(:,1),K_max_L_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_State_yy(:,1),K_max_R_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_State_yy(:,1),K_250_L_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_State_yy(:,1),K_250_R_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_State_yy(:,1),K_10_L_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_State_yy(:,1),K_10_R_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_State_yy(:,1),K_transfer_L_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_State_yy(:,1),K_transfer_R_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_State_yy(:,1),K_worksite_L_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
```
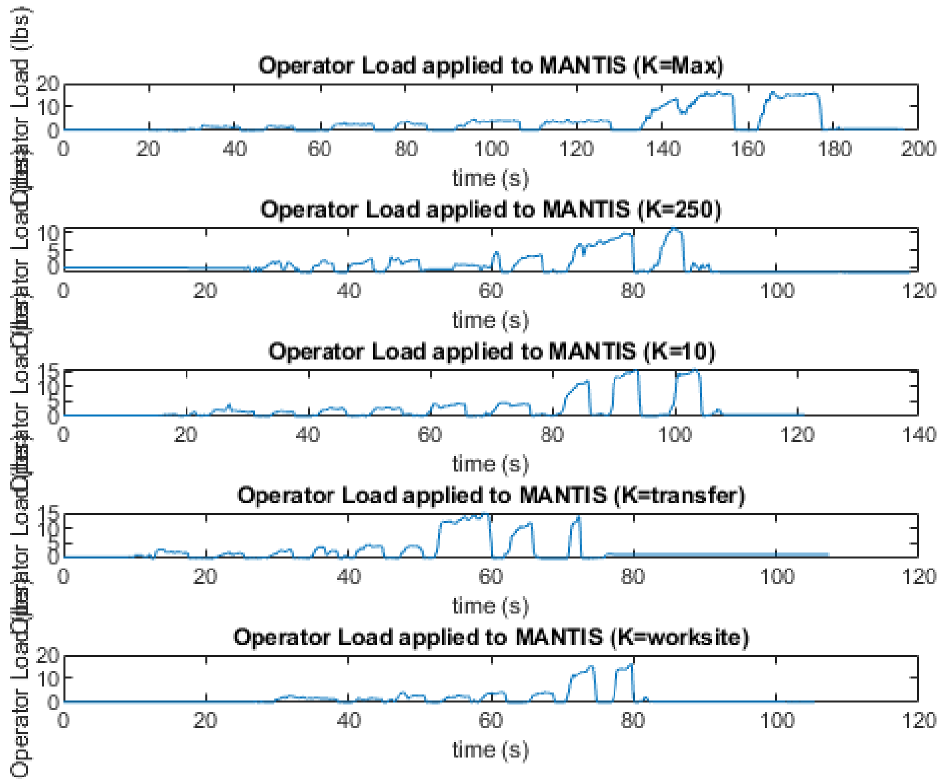
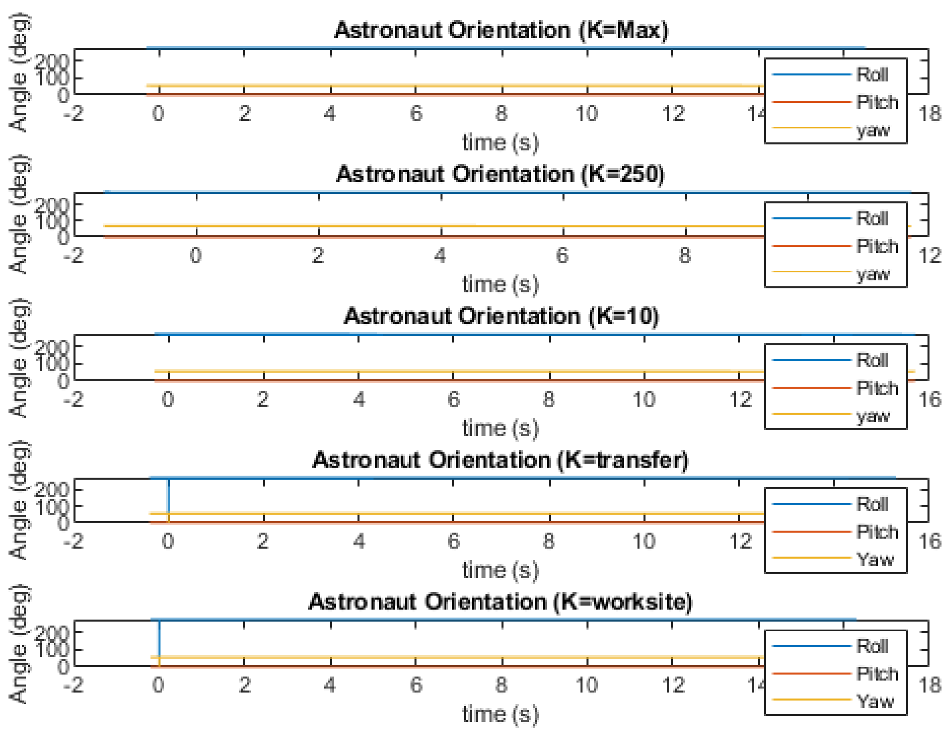
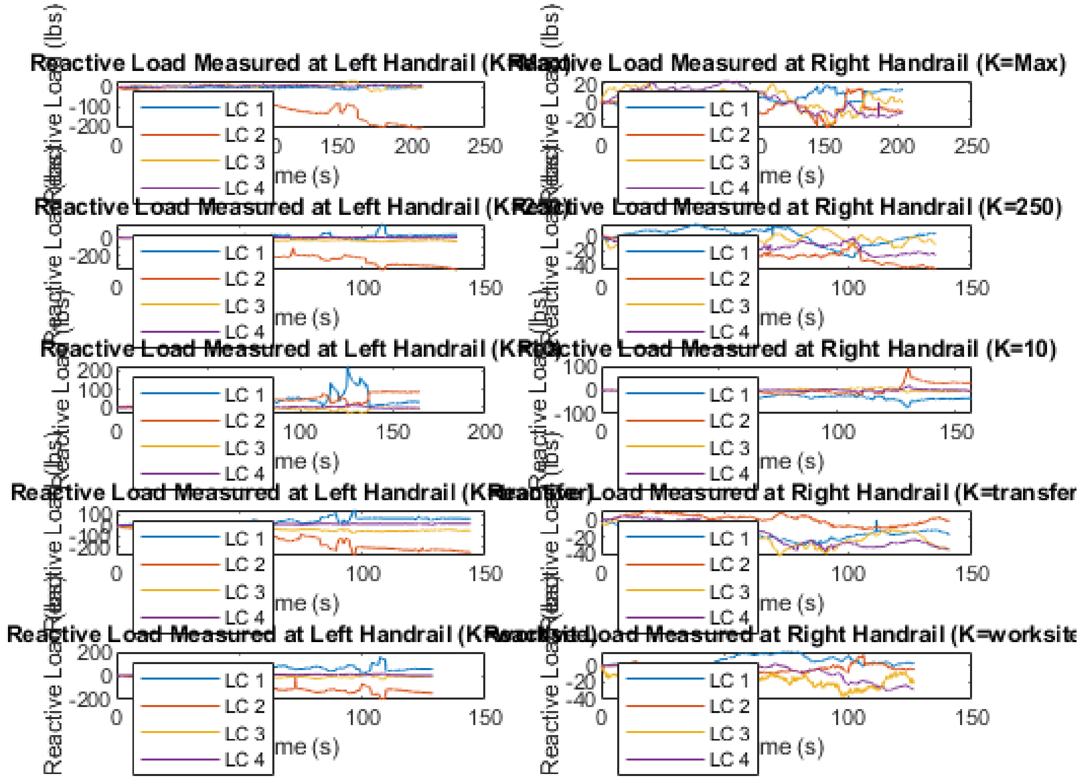
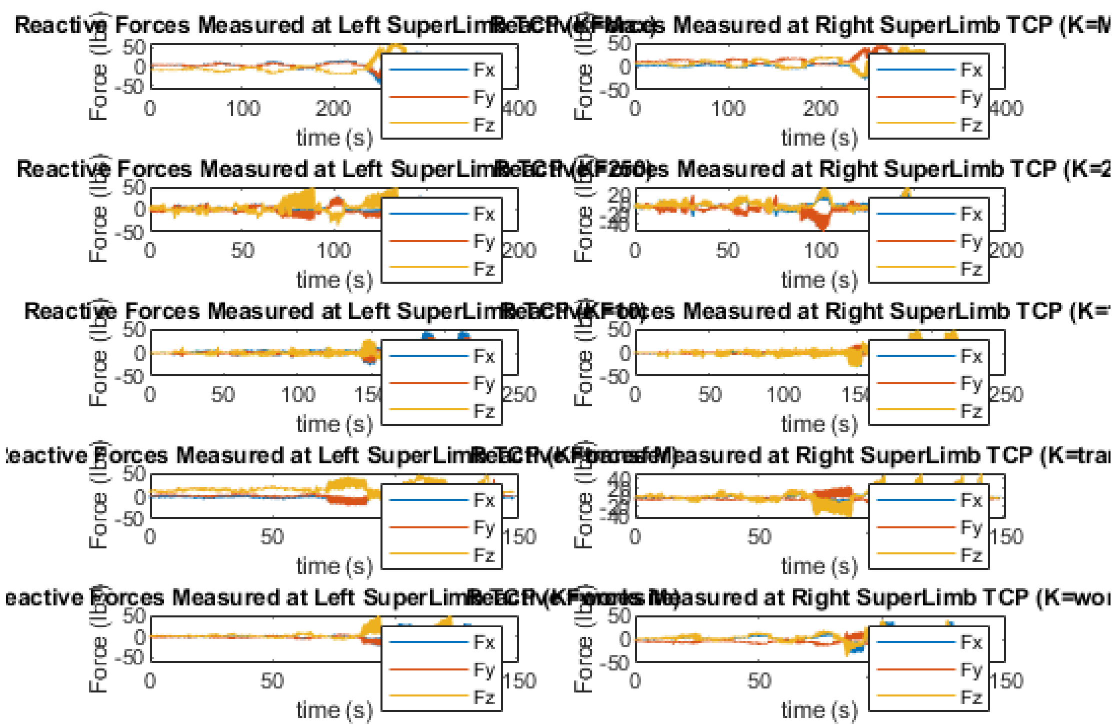

```
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_State_yy(:,1),K_worksite_R_Jt_State_yy(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=worksite)');
```


Operator Load applied to MANTIS (K=Max)
Operator Load applied to MANTIS (K=250)
Operator Load applied to MANTIS (K=10)
Operator Load applied to MANTIS (K=transfer)
Operator Load applied to MANTIS (K=worksite)
Operator Load (lbs)
time (s)

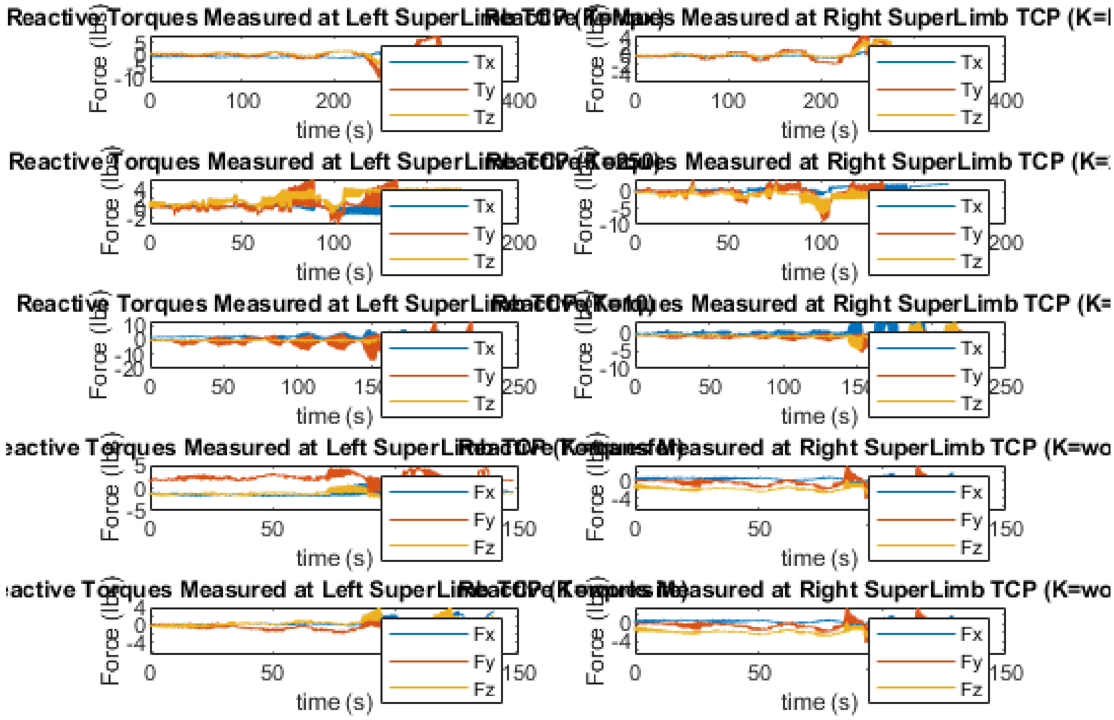

Astronaut Orientation (K=Max)
Astronaut Orientation (K=250)
Astronaut Orientation (K=10)
Astronaut Orientation (K=transfer)
Astronaut Orientation (K=worksite)
Angle (deg)
time (s)
Roll
Pitch
yaw
Yaw

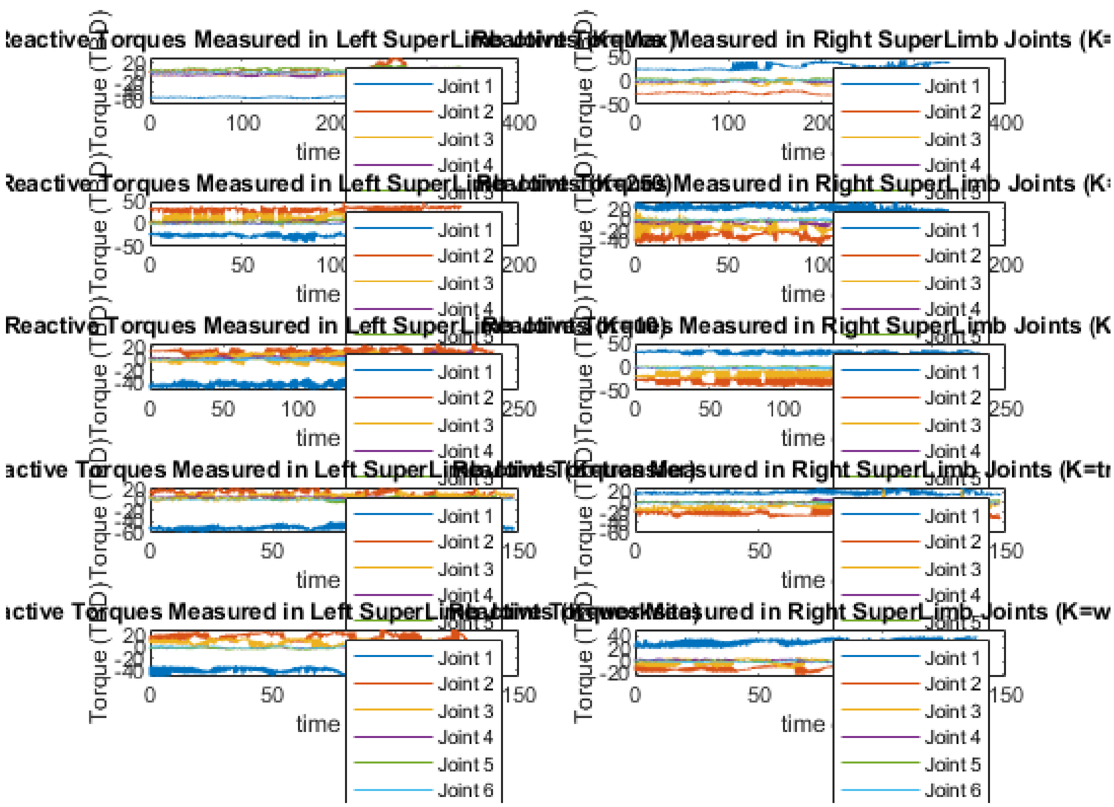


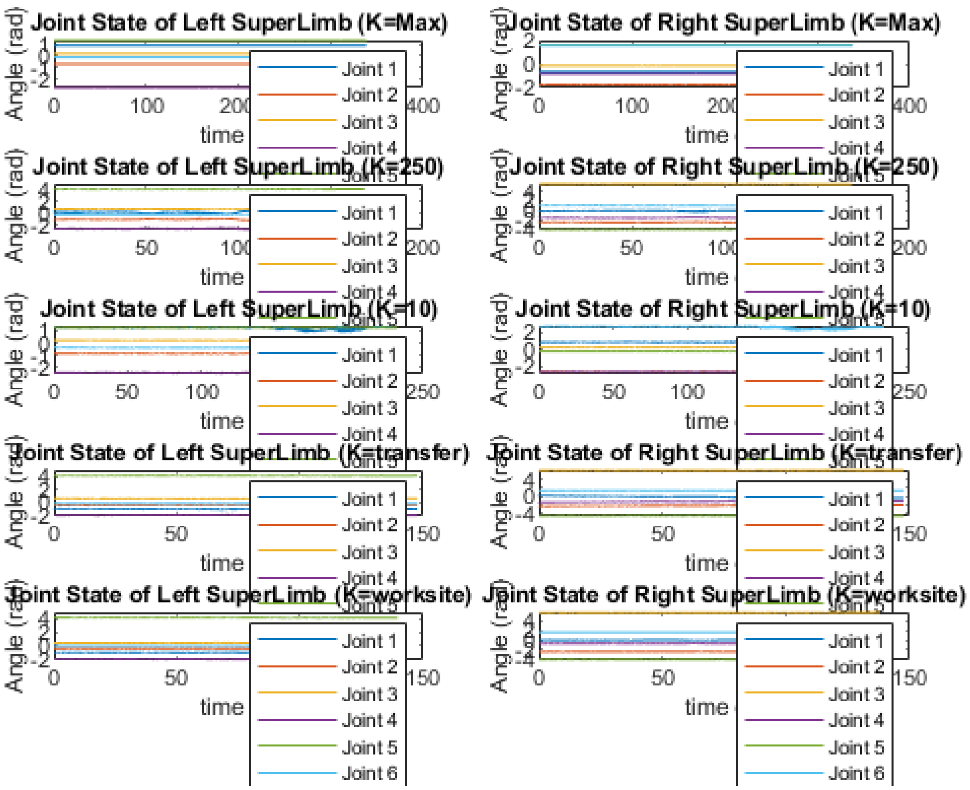
Reactive Load Measured at Right Handrail (K=Max)
Reactive Load Measured at Right Handrail (K=250)
Reactive Load Measured at Right Handrail (K=10)
Reactive Load Measured at Right Handrail (K=transfer
Reactive Load Measured at Left Handrail
Reactive Load (lbs)
LC 1
LC 2
LC 3
LC 4
time (s)



Reactive Forces Measured at Left SuperLimb TCP
Reactive Forces Measured at Right SuperLimb TCP
Force (lbs)
Fx
Fy
Fz
time (s)


Force (lb)
time (s)
Tx
Ty
Tz
Fx
Fy
Fz


Torque (TBD)
time
Joint 1
Joint 2
Joint 3
Joint 4
Joint 5
Joint 6



ZZ DIRECTION OPERATOR APPLIED TORQUE %%

```
%%PROCESSING OF IMU AND OPERATION LOAD CELL DATA%%
K_max_IMU_LC_zz = readmatrix("K_max_pose_2\IMU_LC_Data\test_zz_1_1.csv");
K_250_IMU_LC_zz = readmatrix("K_250_pose_4\IMU_LC_Data\test_zz_3_1.csv");
K_10_IMU_LC_zz = readmatrix("K_10_pose_3\IMU_LC_Data\test_zz_2_1.csv");
K_transfer_IMU_LC_zz = readmatrix("K_Transfer\IMU_LC_Data\Test_zz.csv");
K_worksite_IMU_LC_zz = readmatrix("K_Worksite\IMU_LC_Data\Test_zz.csv");

K_max_IMU_zz = [K_max_IMU_LC_zz(:,3:6)];
K_250_IMU_zz = [K_250_IMU_LC_zz(:,3:6)];
K_10_IMU_zz = [K_10_IMU_LC_zz(:,3:6)];
K_transfer_IMU_zz = [K_transfer_IMU_LC_zz(:,3:6)];
K_worksite_IMU_zz = [K_worksite_IMU_LC_zz(:,3:6)];

K_max_LC_zz = K_max_IMU_LC_zz(:,2:3);
K_250_LC_zz = K_250_IMU_LC_zz(:,2:3);
K_10_LC_zz = K_10_IMU_LC_zz(:,2:3);
K_transfer_LC_zz = K_transfer_IMU_LC_zz(:,2:3);
K_worksite_LC_zz = K_worksite_IMU_LC_zz(:,2:3);

%%PLOT zz OPERATOR LOAD CELL DATA%%
figure(1)
subplot(5,1,1)
plot(K_max_LC_zz(:,1),K_max_LC_zz(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=Max)');
subplot(5,1,2)
plot(K_250_LC_zz(:,1),K_250_LC_zz(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=250)');
subplot(5,1,3)
plot(K_10_LC_zz(:,1),K_10_LC_zz(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
```

```
title('Operator Load applied to MANTIS (K=10)');
subplot(5,1,4)
plot(K_transfer_LC_zz(:,1),K_transfer_LC_zz(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=transfer)');
subplot(5,1,5)
plot(K_worksite_LC_zz(:,1),K_worksite_LC_zz(:,2)),
xlabel('time (s)'), ylabel('Operator Load (lbs)'),
title('Operator Load applied to MANTIS (K=worksite)');

%%PLOT IMU DATA%%
figure(2)
subplot(5,1,1)
plot(K_max_IMU_zz(:,1),K_max_IMU_zz(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=Max)');
subplot(5,1,2)
plot(K_250_IMU_zz(:,1),K_250_IMU_zz(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=250)');
subplot(5,1,3)
plot(K_10_IMU_zz(:,1),K_10_IMU_zz(:,2:4)),
legend('Roll','Pitch','yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=10)');
subplot(5,1,4)
plot(K_transfer_IMU_zz(:,1),K_transfer_IMU_zz(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=transfer)');
subplot(5,1,5)
plot(K_worksite_IMU_zz(:,1),K_worksite_IMU_zz(:,2:4)),
legend('Roll','Pitch','Yaw'),
xlabel('time (s)'), ylabel('Angle (deg)'),
title('Astronaut Orientation (K=worksite)');

%%PROCESSING OF HANDRAIL DATA%%
K_max_R_HR_zz = readmatrix("K_max_pose_2\Handrail_Data\test_zz_1_1_black.csv");
K_max_L_HR_zz = readmatrix("K_max_pose_2\Handrail_Data\test_zz_1_1_white.csv");
K_250_R_HR_zz = readmatrix("K_250_pose_4\Handrail_Data\test_zz_3_1_black.csv");
K_250_L_HR_zz = readmatrix("K_250_pose_4\Handrail_Data\test_zz_3_1_white.csv");
K_10_R_HR_zz = readmatrix("K_10_pose_3\Handrail_Data\test_zz_2_1_black.csv");
K_10_L_HR_zz = readmatrix("K_10_pose_3\Handrail_Data\test_zz_2_1_white.csv");
K_transfer_R_HR_zz = readmatrix("K_Transfer\Handrail_Data\test_zz_black.csv");
K_transfer_L_HR_zz = readmatrix("K_Transfer\Handrail_Data\test_zz_white.csv");
K_worksite_R_HR_zz = readmatrix("K_Worksite\Handrail_Data\test_zz_black.csv");
K_worksite_L_HR_zz = readmatrix("K_Worksite\Handrail_Data\test_zz_white.csv");

%%PLOT HANDRAIL DATA%%
figure(3)
subplot(5,2,1)
plot(K_max_L_HR_zz(:,1),K_max_L_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=Max)');
subplot(5,2,2)
plot(K_max_R_HR_zz(:,1),K_max_R_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=Max)');
```

```
subplot(5,2,3)
plot(K_250_L_HR_zz(:,1),K_250_L_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=250)');
subplot(5,2,4)
plot(K_250_R_HR_zz(:,1),K_250_R_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=250)');
subplot(5,2,5)
plot(K_10_L_HR_zz(:,1),K_10_L_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=10)');
subplot(5,2,6)
plot(K_10_R_HR_zz(:,1),K_10_R_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=10)');
subplot(5,2,7)
plot(K_transfer_L_HR_zz(:,1),K_transfer_L_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_HR_zz(:,1),K_transfer_R_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_HR_zz(:,1),K_worksite_L_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Left Handrail (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_HR_zz(:,1),K_worksite_R_HR_zz(:,2:5));
legend('LC 1','LC 2','LC 3','LC 4','Location','northwest'),
xlabel('time (s)'), ylabel('Reactive Load (lbs)'),
title('Reactive Load Measured at Right Handrail (K=worksite)');

%%PROCESSING OF UR5E DATA%%
K_max_R_FT_zz = readmatrix("K_max_pose_2\UR5e_Data\test_zz_1_1\right_ft_data.csv");
K_max_L_FT_zz = readmatrix("K_max_pose_2\UR5e_Data\test_zz_1_1\left_ft_data.csv");
K_250_R_FT_zz = readmatrix("K_250_pose_4\UR5e_Data\test_zz_3_1\right_ft_data.csv");
K_250_L_FT_zz = readmatrix("K_250_pose_4\UR5e_Data\test_zz_3_1\left_ft_data.csv");
K_10_R_FT_zz = readmatrix("K_10_pose_3\UR5e_Data\test_zz_2_1\right_ft_data.csv");
K_10_L_FT_zz = readmatrix("K_10_pose_3\UR5e_Data\test_zz_2_1\left_ft_data.csv");
K_transfer_R_FT_zz = readmatrix("K_Transfer\UR5e_Data\K_Transfer_ZZ\right_ft_data.csv");
K_transfer_L_FT_zz = readmatrix("K_Transfer\UR5e_Data\K_Transfer_ZZ\left_ft_data.csv");
K_worksite_R_FT_zz = readmatrix("K_Worksite\UR5e_Data\K_Worksite_ZZ\right_ft_data.csv");
K_worksite_L_FT_zz = readmatrix("K_Worksite\UR5e_Data\K_Worksite_ZZ\left_ft_data.csv");

K_max_R_FT_zz = [K_max_R_FT_zz(:,3),K_max_R_FT_zz(:,5:10)];
K_max_L_FT_zz = [K_max_L_FT_zz(:,3),K_max_L_FT_zz(:,5:10)];
K_250_R_FT_zz = [K_250_R_FT_zz(:,3),K_250_R_FT_zz(:,5:10)];
K_250_L_FT_zz = [K_250_L_FT_zz(:,3),K_250_L_FT_zz(:,5:10)];
K_10_R_FT_zz = [K_10_R_FT_zz(:,3),K_10_R_FT_zz(:,5:10)];
K_10_L_FT_zz = [K_10_L_FT_zz(:,3),K_10_L_FT_zz(:,5:10)];
K_transfer_R_FT_zz = [K_transfer_R_FT_zz(:,3),K_transfer_R_FT_zz(:,5:10)];
K_transfer_L_FT_zz = [K_transfer_L_FT_zz(:,3),K_transfer_L_FT_zz(:,5:10)];
K_worksite_R_FT_zz = [K_worksite_R_FT_zz(:,3),K_worksite_R_FT_zz(:,5:10)];
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K_worksite_L_FT_zz = [K_worksite_L_FT_zz(:,3),K_worksite_L_FT_zz(:,5:10)];

K_max_R_Jt_Trq_zz = readmatrix("K_max_pose_2\UR5e_Data\test_zz_1_1\right_joint_torques.csv");
K_max_L_Jt_Trq_zz = readmatrix("K_max_pose_2\UR5e_Data\test_zz_1_1\left_joint_torques.csv");
K_250_R_Jt_Trq_zz = readmatrix("K_250_pose_4\UR5e_Data\test_zz_3_1\right_joint_torques.csv");
K_250_L_Jt_Trq_zz = readmatrix("K_250_pose_4\UR5e_Data\test_zz_3_1\left_joint_torques.csv");
K_10_R_Jt_Trq_zz = readmatrix("K_10_pose_3\UR5e_Data\test_zz_2_1\right_joint_torques.csv");
K_10_L_Jt_Trq_zz = readmatrix("K_10_pose_3\UR5e_Data\test_zz_2_1\left_joint_torques.csv");
K_transfer_R_Jt_Trq_zz = readmatrix("K_Transfer\UR5e_Data\K_Transfer_ZZ\right_joint_torques.csv");
K_transfer_L_Jt_Trq_zz = readmatrix("K_Transfer\UR5e_Data\K_Transfer_ZZ\left_joint_torques.csv");
K_worksite_R_Jt_Trq_zz = readmatrix("K_Worksite\UR5e_Data\K_Worksite_ZZ\right_joint_torques.csv");
K_worksite_L_Jt_Trq_zz = readmatrix("K_Worksite\UR5e_Data\K_Worksite_ZZ\left_joint_torques.csv");

K_max_R_Jt_Trq_zz = K_max_R_Jt_Trq_zz(:,2:8);
K_max_L_Jt_Trq_zz = K_max_L_Jt_Trq_zz(:,2:8);
K_250_R_Jt_Trq_zz = K_250_R_Jt_Trq_zz(:,2:8);
K_250_L_Jt_Trq_zz = K_250_L_Jt_Trq_zz(:,2:8);
K_10_R_Jt_Trq_zz = K_10_R_Jt_Trq_zz(:,2:8);
K_10_L_Jt_Trq_zz = K_10_L_Jt_Trq_zz(:,2:8);
K_transfer_R_Jt_Trq_zz = K_transfer_R_Jt_Trq_zz(:,2:8);
K_transfer_L_Jt_Trq_zz = K_transfer_L_Jt_Trq_zz(:,2:8);
K_worksite_R_Jt_Trq_zz = K_worksite_R_Jt_Trq_zz(:,2:8);
K_worksite_L_Jt_Trq_zz = K_worksite_L_Jt_Trq_zz(:,2:8);

K_max_R_Jt_State_zz = readmatrix("K_max_pose_2\UR5e_Data\test_zz_1_1\right_joint_states.csv");
K_max_L_Jt_State_zz = readmatrix("K_max_pose_2\UR5e_Data\test_zz_1_1\left_joint_states.csv");
K_250_R_Jt_State_zz = readmatrix("K_250_pose_4\UR5e_Data\test_zz_3_1\right_joint_states.csv");
K_250_L_Jt_State_zz = readmatrix("K_250_pose_4\UR5e_Data\test_zz_3_1\left_joint_states.csv");
K_10_R_Jt_State_zz = readmatrix("K_10_pose_3\UR5e_Data\test_zz_2_1\right_joint_states.csv");
K_10_L_Jt_State_zz = readmatrix("K_10_pose_3\UR5e_Data\test_zz_2_1\left_joint_states.csv");
K_transfer_R_Jt_State_zz = readmatrix("K_Transfer\UR5e_Data\K_Transfer_ZZ\right_joint_states.csv");
K_transfer_L_Jt_State_zz = readmatrix("K_Transfer\UR5e_Data\K_Transfer_ZZ\left_joint_states.csv");
K_worksite_R_Jt_State_zz = readmatrix("K_Worksite\UR5e_Data\K_Worksite_ZZ\right_joint_states.csv");
K_worksite_L_Jt_State_zz = readmatrix("K_Worksite\UR5e_Data\K_Worksite_ZZ\left_joint_states.csv");

K_max_R_Jt_State_zz = [K_max_R_Jt_State_zz(:,3),K_max_R_Jt_State_zz(:,10:15)];
K_max_L_Jt_State_zz = [K_max_L_Jt_State_zz(:,3),K_max_L_Jt_State_zz(:,10:15)];
K_250_R_Jt_State_zz = [K_250_R_Jt_State_zz(:,3),K_250_R_Jt_State_zz(:,10:15)];
K_250_L_Jt_State_zz = [K_250_L_Jt_State_zz(:,3),K_250_L_Jt_State_zz(:,10:15)];
K_10_R_Jt_State_zz = [K_10_R_Jt_State_zz(:,3),K_10_R_Jt_State_zz(:,10:15)];
K_10_L_Jt_State_zz = [K_10_L_Jt_State_zz(:,3),K_10_L_Jt_State_zz(:,10:15)];
K_transfer_R_Jt_State_zz = [K_transfer_R_Jt_State_zz(:,3),K_transfer_R_Jt_State_zz(:,10:15)];
K_transfer_L_Jt_State_zz = [K_transfer_L_Jt_State_zz(:,3),K_transfer_L_Jt_State_zz(:,10:15)];
K_worksite_R_Jt_State_zz = [K_worksite_R_Jt_State_zz(:,3),K_worksite_R_Jt_State_zz(:,10:15)];
K_worksite_L_Jt_State_zz = [K_worksite_L_Jt_State_zz(:,3),K_worksite_L_Jt_State_zz(:,10:15)];

%%PLOT UR5E DATA%%
figure(4)
subplot(5,2,1)
plot(K_max_L_FT_zz(:,1),K_max_L_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_zz(:,1),K_max_R_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_zz(:,1),K_250_L_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
```
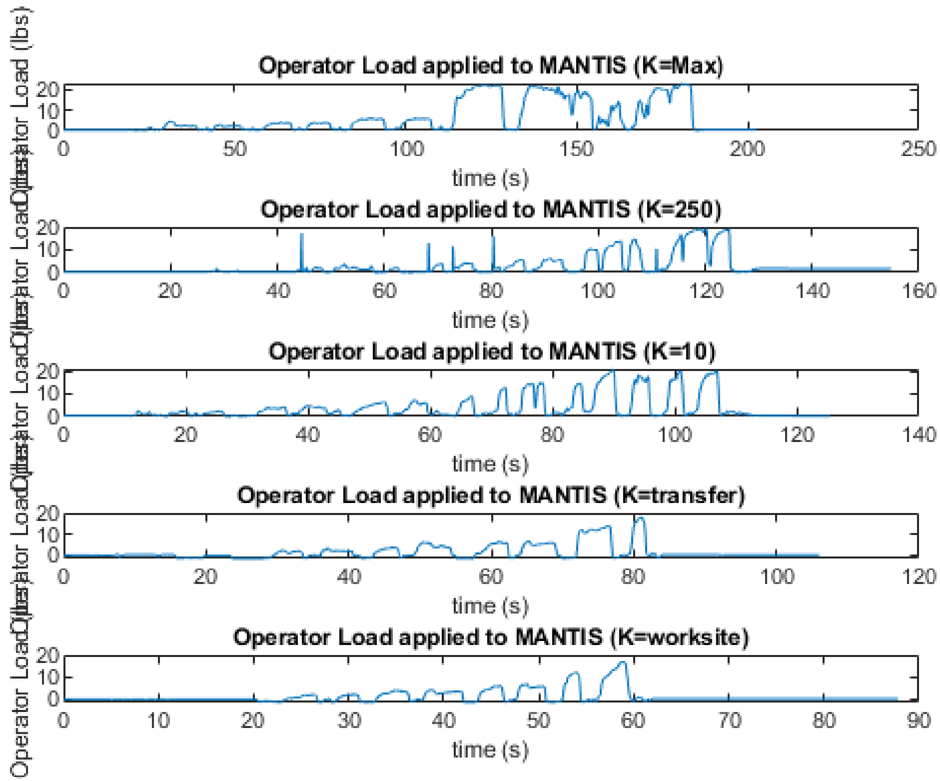
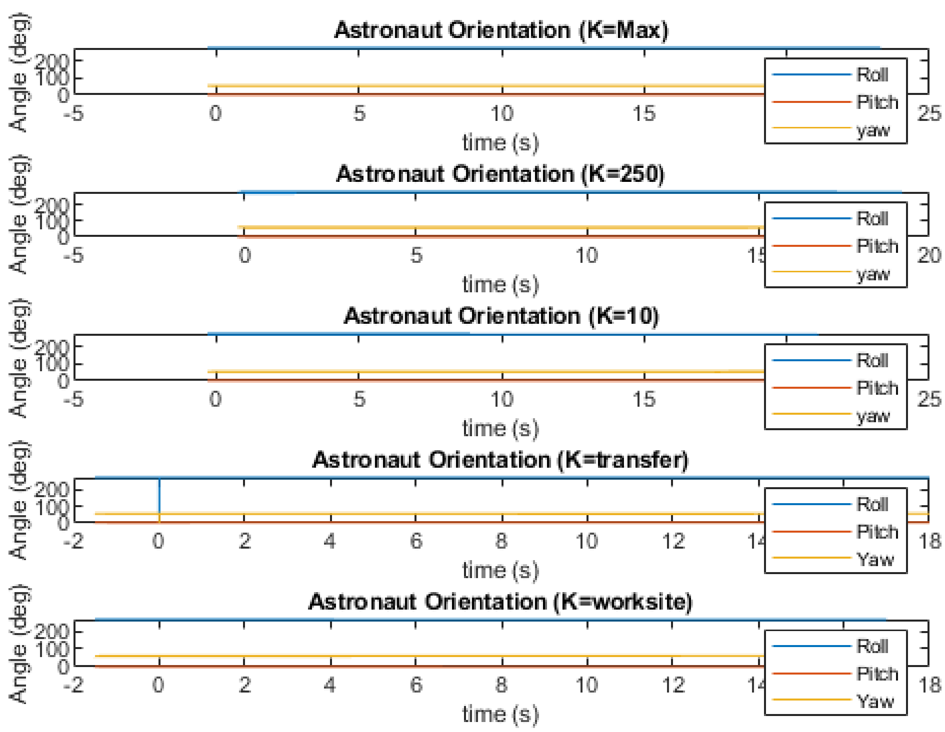

```
title('Reactive Forces Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_zz(:,1),K_250_R_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_zz(:,1),K_10_L_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_zz(:,1),K_10_R_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_zz(:,1),K_transfer_L_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_FT_zz(:,1),K_transfer_R_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_FT_zz(:,1),K_worksite_L_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_zz(:,1),K_worksite_R_FT_zz(:,2:4));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Forces Measured at Right SuperLimb TCP (K=worksite)');

figure(5)
subplot(5,2,1)
plot(K_max_L_FT_zz(:,1),K_max_L_FT_zz(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=Max)');
subplot(5,2,2)
plot(K_max_R_FT_zz(:,1),K_max_R_FT_zz(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=Max)');
subplot(5,2,3)
plot(K_250_L_FT_zz(:,1),K_250_L_FT_zz(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=250)');
subplot(5,2,4)
plot(K_250_R_FT_zz(:,1),K_250_R_FT_zz(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=250)');
subplot(5,2,5)
plot(K_10_L_FT_zz(:,1),K_10_L_FT_zz(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
```

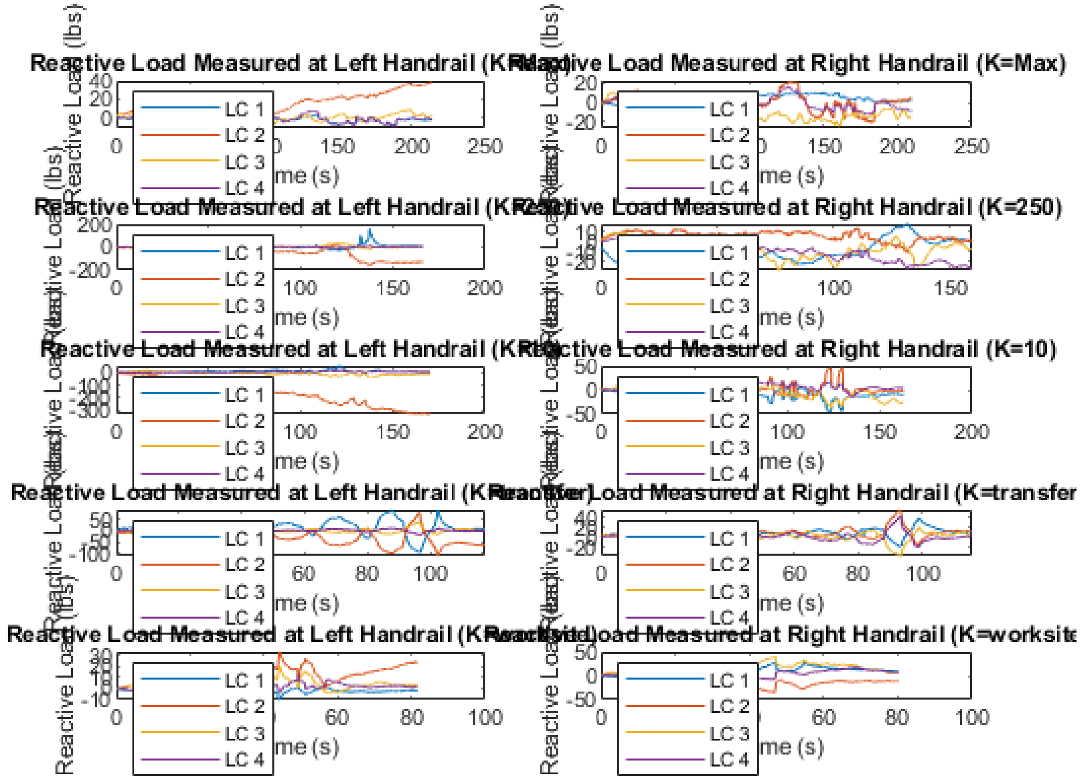
```
title('Reactive Torques Measured at Left SuperLimb TCP (K=10)');
subplot(5,2,6)
plot(K_10_R_FT_zz(:,1),K_10_R_FT_zz(:,5:7));
legend('Tx','Ty','Tz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=10)');
subplot(5,2,7)
plot(K_transfer_L_FT_zz(:,1),K_transfer_L_FT_zz(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=transfer)');
subplot(5,2,8)
plot(K_worksite_R_FT_zz(:,1),K_worksite_R_FT_zz(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');
subplot(5,2,9)
plot(K_worksite_L_FT_zz(:,1),K_worksite_L_FT_zz(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Left SuperLimb TCP (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_FT_zz(:,1),K_worksite_R_FT_zz(:,5:7));
legend('Fx','Fy','Fz'),
xlabel('time (s)'), ylabel('Force (lbs)'),
title('Reactive Torques Measured at Right SuperLimb TCP (K=worksite)');

figure(6)
subplot(5,2,1)
plot(K_max_L_Jt_Trq_zz(:,1),K_max_L_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_Trq_zz(:,1),K_max_R_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_Trq_zz(:,1),K_250_L_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_Trq_zz(:,1),K_250_R_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_Trq_zz(:,1),K_10_L_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_Trq_zz(:,1),K_10_R_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_Trq_zz(:,1),K_transfer_L_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
```

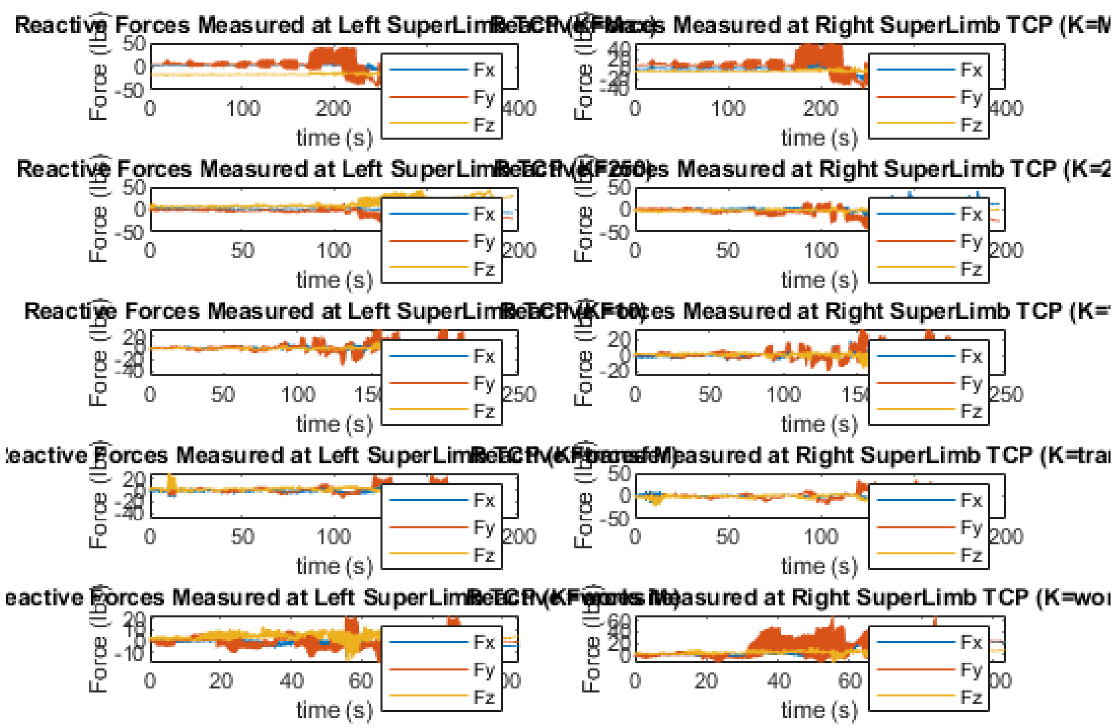
```
title('Reactive Torques Measured in Left SuperLimb Joints (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_Trq_zz(:,1),K_transfer_R_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_Trq_zz(:,1),K_worksite_L_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Left SuperLimb Joints (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_Trq_zz(:,1),K_worksite_R_Jt_Trq_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Torque (TBD)'),
title('Reactive Torques Measured in Right SuperLimb Joints (K=worksite)');

figure(7)
subplot(5,2,1)
plot(K_max_L_Jt_State_zz(:,1),K_max_L_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=Max)');
subplot(5,2,2)
plot(K_max_R_Jt_State_zz(:,1),K_max_R_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=Max)');
subplot(5,2,3)
plot(K_250_L_Jt_State_zz(:,1),K_250_L_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=250)');
subplot(5,2,4)
plot(K_250_R_Jt_State_zz(:,1),K_250_R_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=250)');
subplot(5,2,5)
plot(K_10_L_Jt_State_zz(:,1),K_10_L_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=10)');
subplot(5,2,6)
plot(K_10_R_Jt_State_zz(:,1),K_10_R_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=10)');
subplot(5,2,7)
plot(K_transfer_L_Jt_State_zz(:,1),K_transfer_L_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Left SuperLimb (K=transfer)');
subplot(5,2,8)
plot(K_transfer_R_Jt_State_zz(:,1),K_transfer_R_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=transfer)');
subplot(5,2,9)
plot(K_worksite_L_Jt_State_zz(:,1),K_worksite_L_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
```

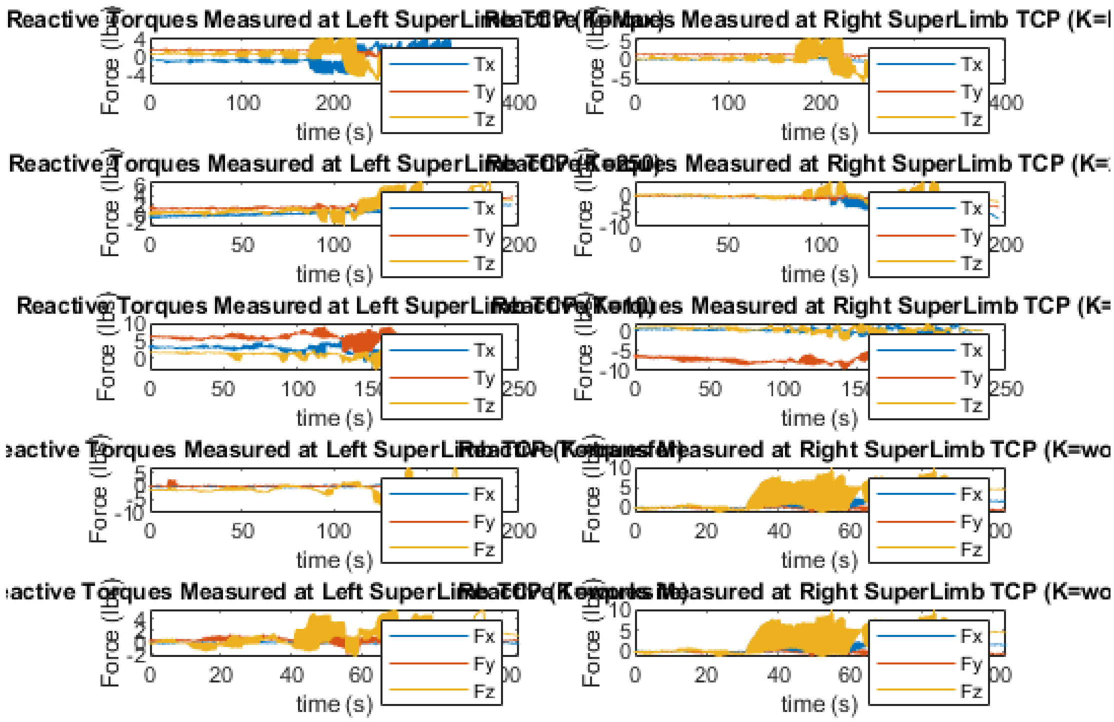
```
title('Joint State of Left SuperLimb (K=worksite)');
subplot(5,2,10)
plot(K_worksite_R_Jt_State_zz(:,1),K_worksite_R_Jt_State_zz(:,2:7));
legend('Joint 1','Joint 2','Joint 3','Joint 4','Joint 5','Joint 6'),
xlabel('time (s)'), ylabel('Angle (rad)'),
title('Joint State of Right SuperLimb (K=worksite)');
```

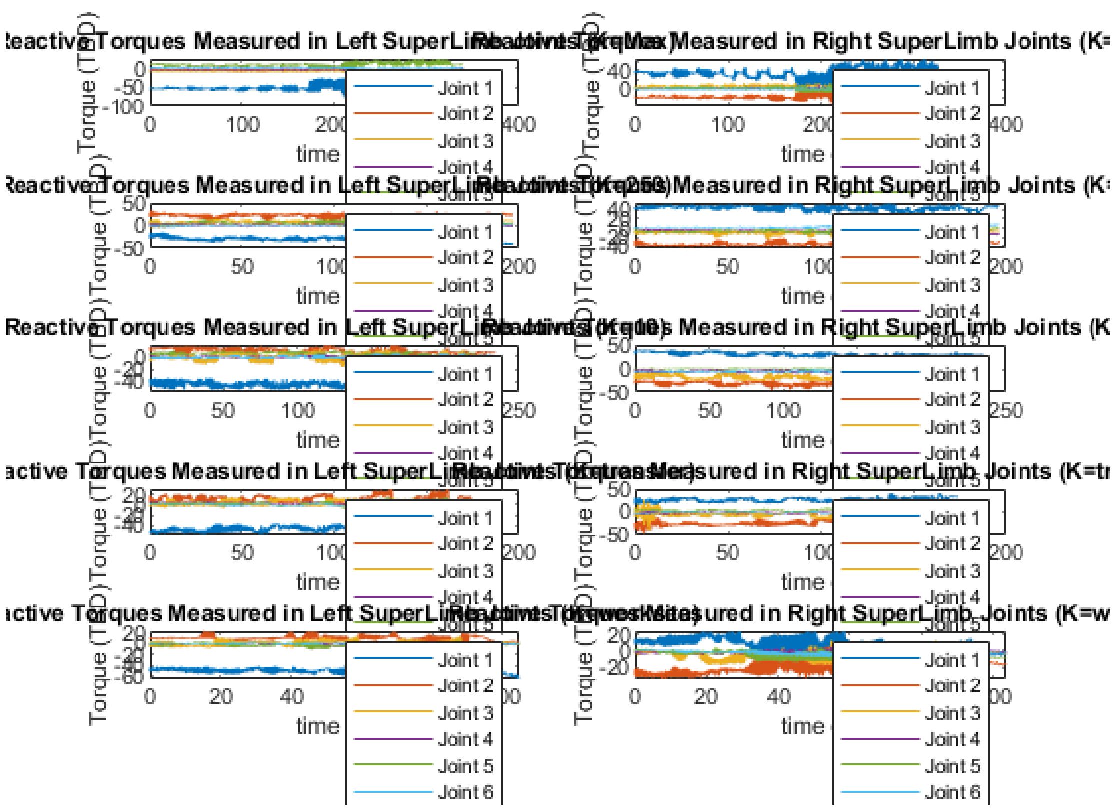

Operator Load applied to MANTIS (K=Max)
Operator Load applied to MANTIS (K=250)
Operator Load applied to MANTIS (K=10)
Operator Load applied to MANTIS (K=transfer)
Operator Load applied to MANTIS (K=worksite)
Operator Load (lbs)
time (s)

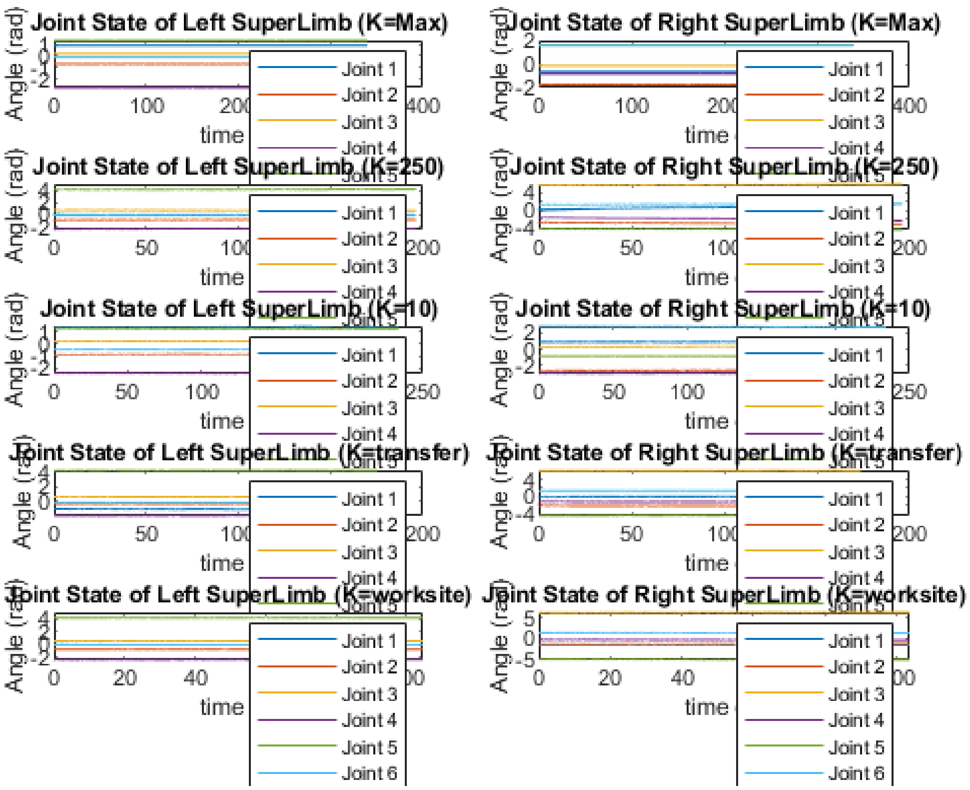

Astronaut Orientation (K=Max)
Astronaut Orientation (K=250)
Astronaut Orientation (K=10)
Astronaut Orientation (K=transfer)
Astronaut Orientation (K=worksite)
Angle (deg)
time (s)
Roll
Pitch
yaw
Yaw


Reactive Load Measured at Right Handrail (K=Max)
Reactive Load Measured at Right Handrail (K=250)
Reactive Load Measured at Right Handrail (K=10)
Reactive Load (lbs)
LC 1
LC 2
LC 3
LC 4
me (s)


Force (lbs)
time (s)
Fx
Fy
Fz


Reactive Torques Measured at Left SuperLimb TCP
Reactive Torques Measured at Right SuperLimb TCP
Force (lb)
time (s)
Tx
Ty
Tz
Fx
Fy
Fz


Reactive Torques Measured in Left SuperLimb Joints
Reactive Torques Measured in Right SuperLimb Joints
time
Joint 1
Joint 2
Joint 3
Joint 4
Joint 5
Joint 6



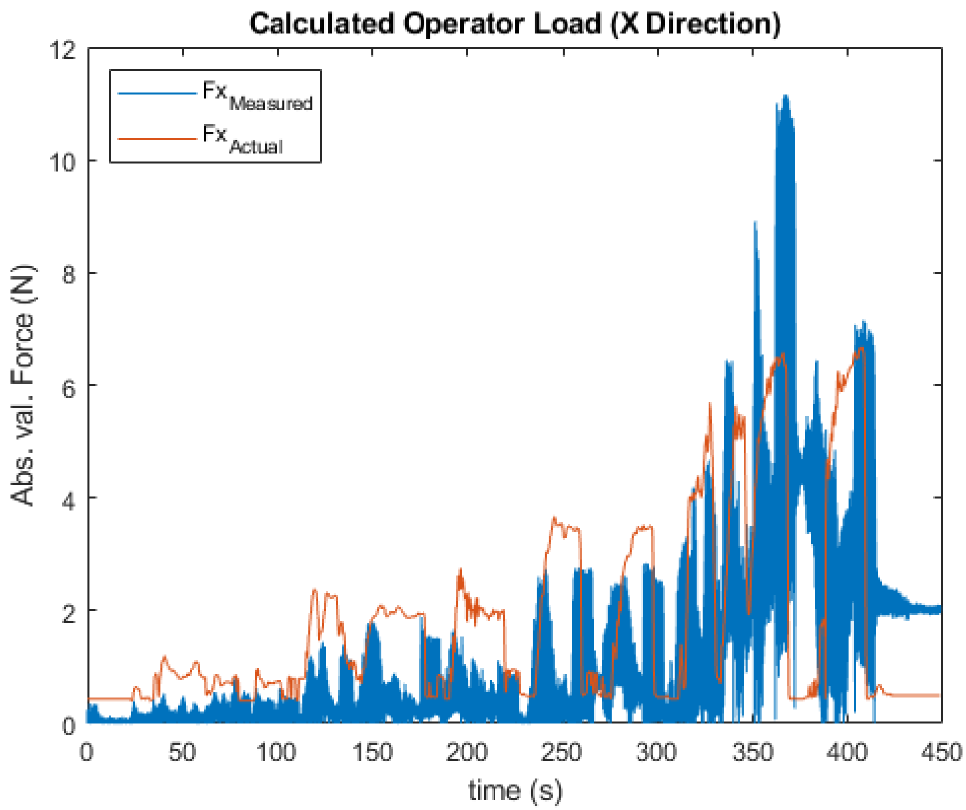
PROCESS DATA %%

Individually analyze graphs and make visual observation on reactive loads

Build a table from scratch to identify reactive loads wrt operator loads

```
%Assign Specific Joints angles from test
theta_L = K_max_L_Jt_State_x(:,2:7);
theta_R = K_max_R_Jt_State_x(:,2:7);

%Assign Specific Forces/Torques from test
LC = K_max_LC_x;
FT_L = K_max_L_FT_x(:,2:7);
FT_R = K_max_R_FT_x(:,2:7);
%FT_L_time = K_max_L_FT_x(:,1);
%FT_R_time = K_max_R_FT_x(:,1);

%TEMPORARY OVERRIDE - DELETE LATER
FT_L_time = K_max_L_FT_x(:,1);
FT_R_time = K_max_R_FT_x(:,1);

%UR5e physical data
%Linkage lengths (m)
l_UR5e = [152.4,89.2,425,392,109.3,94.75,82.5]/1000;
%Rotation matrices for each joint
for i = 1:length(theta_L)
    Rx1_L(:,:,i) = [1,0,0;0,cos(theta_L(i,1)),-sin(theta_L(i,1));0,sin(theta_L(i,1)),cos(theta_L(i,1))];
    Rz2_L(:,:,i) = [cos(theta_L(i,2)),-sin(theta_L(i,2)),0;sin(theta_L(i,2)),cos(theta_L(i,2)),0;0,0,1];
    Rz3_L(:,:,i) = [cos(theta_L(i,3)),-sin(theta_L(i,3)),0;sin(theta_L(i,3)),cos(theta_L(i,3)),0;0,0,1];
    Rz4_L(:,:,i) = [cos(theta_L(i,4)),-sin(theta_L(i,4)),0;sin(theta_L(i,4)),cos(theta_L(i,4)),0;0,0,1];
    Rx5_L(:,:,i) = [1,0,0;0,cos(theta_L(i,5)),-sin(theta_L(i,5));0,sin(theta_L(i,5)),cos(theta_L(i,5))];
    Rz6_L(:,:,i) = [cos(theta_L(i,6)),-sin(theta_L(i,6)),0;sin(theta_L(i,6)),cos(theta_L(i,6)),0;0,0,1];
    r_L(i,:) = [l_UR5e(1);0;0]+(Rx1_L(:,:,i)*[l_UR5e(2);0;0])+(Rx1_L(:,:,i)*Rz2_L(:,:,i)*[l_UR5e(3);0;0])+...
    (Rx1_L(:,:,i)*Rz2_L(:,:,i)*Rz3_L(:,:,i)*[l_UR5e(4);0;0])+...
```

```matlab
    (Rx1_L(:,:,i)*Rz2_L(:,:,i)*Rz3_L(:,:,i)*Rz4_L(:,:,i)*[0;0;l_UR5e(5)])+...
    (Rx1_L(:,:,i)*Rz2_L(:,:,i)*Rz3_L(:,:,i)*Rz4_L(:,:,i)*Rx5_L(:,:,i)*[l_UR5e(6);0;0])+...
    (Rx1_L(:,:,i)*Rz2_L(:,:,i)*Rz3_L(:,:,i)*Rz4_L(:,:,i)*Rx5_L(:,:,i)*Rz6_L(:,:,i)*[0;0;l_UR5e(7)]);
    r_L(i,:) = r_L(i,:);
end
for i = 1:length(theta_R)
    Rx1_R(:,:,i) = [1,0,0;0,cos(theta_R(i,1)),-sin(theta_R(i,1));0,sin(theta_R(i,1)),cos(theta_R(i,1))];
    Rz2_R(:,:,i) = [cos(theta_R(i,2)),-sin(theta_R(i,2)),0;sin(theta_R(i,2)),cos(theta_R(i,2)),0;0,0,1];
    Rz3_R(:,:,i) = [cos(theta_R(i,3)),-sin(theta_R(i,3)),0;sin(theta_R(i,3)),cos(theta_R(i,3)),0;0,0,1];
    Rz4_R(:,:,i) = [cos(theta_R(i,4)),-sin(theta_R(i,4)),0;sin(theta_R(i,4)),cos(theta_R(i,4)),0;0,0,1];
    Rx5_R(:,:,i) = [1,0,0;0,cos(theta_R(i,5)),-sin(theta_R(i,5));0,sin(theta_R(i,5)),cos(theta_R(i,5))];
    Rz6_R(:,:,i) = [cos(theta_R(i,6)),-sin(theta_R(i,6)),0;sin(theta_R(i,6)),cos(theta_R(i,6)),0;0,0,1];
    r_R(i,:) = [l_UR5e(1);0;0]+(Rx1_R(:,:,i)*[l_UR5e(2);0;0])+(Rx1_R(:,:,i)*Rz2_R(:,:,i)*[l_UR5e(3);0;0])+...
    (Rx1_R(:,:,i)*Rz2_R(:,:,i)*Rz3_R(:,:,i)*[l_UR5e(4);0;0])+...
    (Rx1_R(:,:,i)*Rz2_R(:,:,i)*Rz3_R(:,:,i)*Rz4_R(:,:,i)*[0;0;l_UR5e(5)])+...
    (Rx1_R(:,:,i)*Rz2_R(:,:,i)*Rz3_R(:,:,i)*Rz4_R(:,:,i)*Rx5_R(:,:,i)*[l_UR5e(6);0;0])+...
    (Rx1_R(:,:,i)*Rz2_R(:,:,i)*Rz3_R(:,:,i)*Rz4_R(:,:,i)*Rx5_R(:,:,i)*Rz6_R(:,:,i)*[0;0;l_UR5e(7)]);
    r_R(i,:) = r_R(i,:);
end

%Calculate F_h based off pose data
for i = 1:length(theta_L)
    s_L(:,:,i) = [0,-r_L(i,3),r_L(i,2);r_L(i,3),0,-r_L(i,1);-r_L(i,2),r_L(i,1),0];
    S_L(:,:,i) = [eye(3),zeros(3);s_L(:,:,i),eye(3)];
end
for i = 1:length(theta_R)
    s_R(:,:,i) = [0,-r_R(i,3),r_R(i,2);r_R(i,3),0,-r_R(i,1);-r_R(i,2),r_R(i,1),0];
    S_R(:,:,i) = [eye(3),zeros(3);s_R(:,:,i),eye(3)];
end
if (length(FT_L) > length(FT_R))
    F_h_size = length(FT_R);
    F_h_time = FT_R_time;
else
    F_h_size = length(FT_L);
    F_h_time = FT_L_time;
end
for i = 1:F_h_size
    F_h(i,:) = -(S_R(:,:,i)*transpose(FT_R(i,:)))-(S_L(:,:,i)*transpose(FT_L(i,:)));
end

figure(8)
plot(F_h_time,(abs(F_h(:,4)-F_h(1,4))*0.2248090795));
hold on
plot(LC(:,1),(LC(:,2)*0.3048)+0.43);
legend('Fx_{Measured}','Fx_{Actual}','location','NorthWest'),
xlabel('time (s)'), ylabel('Abs. val. Force (N)'),
title('Calculated Operator Load (X Direction)');
```



Published with MATLAB® R2022a

Contents

DATA PROCESSOR FOR STATIC BRACING PERFORMANCE WITH COMPLIANCE CONTROLLER

```
clc;
clear;
```

IMPORT URDF OF UR5e

```
UR5e = loadrobot("universalUR5e");
```

IMPORT UR5e DATA

```
K_max = readmatrix("G:\MIT\d-Lab\xEMU_SuperLIMBs\Testing_Data\K_max_pose_2\UR5e_Data\test_z_1_1\left_joint_states.csv");
K_250 = readmatrix("G:\MIT\d-Lab\xEMU_SuperLIMBs\Testing_Data\K_250_pose_4\UR5e_Data\test_z_3_1\left_joint_states.csv");
K_100 = readmatrix("G:\MIT\d-Lab\xEMU_SuperLIMBs\Testing_Data\K_Transfer\UR5e_Data\K_Transfer_Z\left_joint_states.csv");
K_10 = readmatrix("G:\MIT\d-Lab\xEMU_SuperLIMBs\Testing_Data\K_10_pose_3\UR5e_Data\test_z_2_1\left_joint_states.csv");
```

FK SOLVER

```
Transform = zeros(4,4);
Position_K_max = zeros(3,length(K_max));
for i = 1:length(K_max)
    Pose_K_max = struct('JointName',{'shoulder_pan_joint','shoulder_lift_joint','elbow_joint','wrist_1_joint','wrist_2_joint','wrist_3_joint'}, ...
        'JointPosition',{K_max(i,22),K_max(i,23),K_max(i,24),K_max(i,25),K_max(i,26),K_max(i,27)});
    Transform(:,:) = getTransform(UR5e,Pose_K_max,'tool0');
    Position_K_max(:,i) = Transform(1:3,4);
end

Position_K_250 = zeros(3,length(K_250));
for i = 1:length(K_250)
    Pose_K_250 = struct('JointName',{'shoulder_pan_joint','shoulder_lift_joint','elbow_joint','wrist_1_joint','wrist_2_joint','wrist_3_joint'}, ...
        'JointPosition',{K_250(i,22),K_250(i,23),K_250(i,24),K_250(i,25),K_250(i,26),K_250(i,27)});
    Transform(:,:) = getTransform(UR5e,Pose_K_250,'tool0');
    Position_K_250(:,i) = Transform(1:3,4);
end

Position_K_100 = zeros(3,length(K_100));
for i = 1:length(K_100)
    Pose_K_100 = struct('JointName',{'shoulder_pan_joint','shoulder_lift_joint','elbow_joint','wrist_1_joint','wrist_2_joint','wrist_3_joint'}, ...
        'JointPosition',{K_100(i,22),K_100(i,23),K_100(i,24),K_100(i,25),K_100(i,26),K_100(i,27)});
    Transform(:,:) = getTransform(UR5e,Pose_K_100,'tool0');
    Position_K_100(:,i) = Transform(1:3,4);
end

Position_K_10 = zeros(3,length(K_10));
for i = 1:length(K_10)
    Pose_K_10 = struct('JointName',{'shoulder_pan_joint','shoulder_lift_joint','elbow_joint','wrist_1_joint','wrist_2_joint','wrist_3_joint'}, ...
        'JointPosition',{K_10(i,22),K_10(i,23),K_10(i,24),K_10(i,25),K_10(i,26),K_10(i,27)});
    Transform(:,:) = getTransform(UR5e,Pose_K_10,'tool0');
    Position_K_10(:,i) = Transform(1:3,4);
end
```

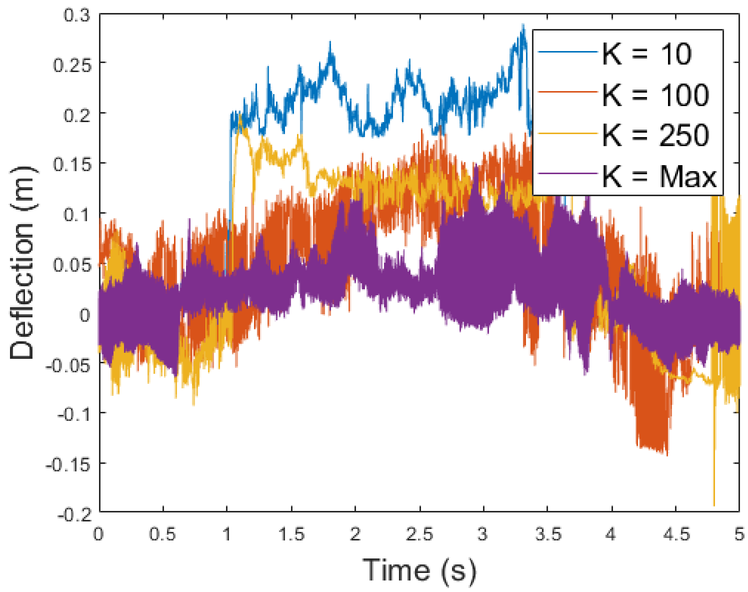
PROCESS DATA

```
Defl_K_max = sqrt((Position_K_max(1,:).^2)+(Position_K_max(2,:).^2)+(Position_K_max(3,:).^2));
Defl_K_max = Defl_K_max - Defl_K_max(1);
Defl_K_250 = sqrt((Position_K_250(1,:).^2)+(Position_K_250(2,:).^2)+(Position_K_250(3,:).^2));
Defl_K_250 = Defl_K_250 - Defl_K_250(17957);
Defl_K_100 = sqrt((Position_K_100(1,:).^2)+(Position_K_100(2,:).^2)+(Position_K_100(3,:).^2));
Defl_K_100 = Defl_K_100 - Defl_K_100(1);
Defl_K_10 = sqrt((Position_K_10(1,:).^2)+(Position_K_10(2,:).^2)+(Position_K_10(3,:).^2));
Defl_K_10 = Defl_K_10 - Defl_K_10(1);
```

```
Defl_K_max(44386:length(Defl_K_max)) = [];
Defl_K_max(1:22970) = [];
Defl_K_max = Defl_K_max - 2*Defl_K_max(1);

Defl_K_250(22500:length(Defl_K_250)) = [];
Defl_K_250(1:17250) = [];
Defl_K_250 = Defl_K_250 - 2*Defl_K_250(1);
% Defl_K_250(1:1000) = Defl_K_250(1:1000) - Defl_K_250(1);
% Defl_K_250(8000:length(Defl_K_250)) = Defl_K_250(8000:length(Defl_K_250)) - Defl_K_250(length(Defl_K_250))/1.5;
% Defl_K_250(10000:length(Defl_K_250)) = [];
for i = length(Defl_K_250)-100:-1:470
    if Defl_K_250(i) < 0.1
        Defl_K_250(i) = [];
    end
end
for i = 1661:length(Defl_K_250)
    Defl_K_250(i) = -Defl_K_250(i) + 0.15;
end

Defl_K_100(39000:length(Defl_K_100)) = [];
Defl_K_100(1:37000) = [];
% Defl_K_100 = Defl_K_100 - Defl_K_100(1);
% for i = length(Defl_K_100)-300:-1:250
%     if Defl_K_100(i) < 0.125
%         Defl_K_100(i) = [];
%     end
% end
% for i = length(Defl_K_100)-300:-1:1
%     if Defl_K_100(i) < -0.025
%         Defl_K_100(i) = [];
%     end
% end

Defl_K_10(79046:length(Defl_K_10)) = [];
Defl_K_10(1:75232) = [];
Defl_K_10 = Defl_K_10 - Defl_K_10(1);
% % Defl_K_10(6500:length(Defl_K_10)) = [];
% Defl_K_10(3500:length(Defl_K_10)) = Defl_K_10(3500:length(Defl_K_10)) - Defl_K_10(3749)/2;
for i = length(Defl_K_10)-500:-1:626
    if Defl_K_10(i) < 0.175
        Defl_K_10(i) = [];
    end
end
Defl_K_10(1:250) = [];
```

PLOT DATA

```
t_max = linspace(0,5,length(Defl_K_max));
t_250 = linspace(0,5,length(Defl_K_250));
t_100 = linspace(0,5,length(Defl_K_100));
t_10 = linspace(0,5,length(Defl_K_10));

figure(1)
plot(t_10,Defl_K_10);
hold on
plot(t_100,Defl_K_100);
hold on
plot(t_250,Defl_K_250);
hold on
plot(t_max,Defl_K_max);
legend('K = 10','K = 100','K = 250','K = Max', 'FontSize', 16);
xlabel('Time (s)', 'FontSize', 16);
ylabel('Deflection (m)', 'FontSize', 16);
```



TRIM DATA

```
for i = 1:length(Defl_K_max)
if rem(i,2) == 0
Defl_K_max(i) = [];
t_max(i) = [];
end
if i >= length(Defl_K_max)
    break
end
end
```

```
for i = 1:length(Defl_K_100)
if rem(i,2) == 0
Defl_K_100(i) = [];
t_100(i) = [];
end
if i >= length(Defl_K_100)
    break
end
end
```

```
for i = 1:length(Defl_K_10)
if rem(i,2) == 0
Defl_K_10(i) = [];
t_10(i) = [];
end
if i >= length(Defl_K_10)
    break
end
end
```

```
for i = 1:length(Defl_K_250)
if rem(i,2) == 0
Defl_K_250(i) = [];
t_250(i) = [];
end
if i >= length(Defl_K_250)
    break
end
end
```

ANIMATE DATA

figure(2) pause(10); for i = 1:length(Defl_K_max) plot(t_max(1:i),Defl_K_max(1:i),'color','#7E2F8E'); ylim([-0.2 0.5]); xlim([0 5]); xlabel('Time (s)', 'FontSize', 16); ylabel('Deflection (m)', 'FontSize', 16); hold on pause(0.0001); end pause(1); for i = 1:length(Defl_K_250) plot(t_250(1:i),Defl_K_250(1:i),'color','#EDB120'); ylim([-0.2 0.5]); xlim([0 5]); xlabel('Time (s)', 'FontSize', 16); ylabel('Deflection (m)', 'FontSize', 16); hold on pause(0.0001); end pause(1); for i = 1:length(Defl_K_10) plot(t_10(1:i),Defl_K_10(1:i),'color','#0072BD'); ylim([-0.2 0.5]); xlim([0 5]); xlabel('Time (s)', 'FontSize', 16); ylabel('Deflection (m)', 'FontSize', 16); hold on pause(0.0001); end

Contents

ADMITTANCE CONTROL DATA PROCESSOR / EVALUATE EFFECTIVE WORK

```
clc;
clear;
```

READ CSV FILES

```
Control = readmatrix("K_P_None.csv");
K_p_1 = readmatrix("K_P_1.csv");
K_p_1_5 = readmatrix("K_P_1_5.csv");
K_p_2 = readmatrix("K_P_2.csv");
K_p_3 = readmatrix("K_P_3.csv");
K_p_5 = readmatrix("K_P_5.csv");
K_p_10 = readmatrix("K_P_10.csv");
K_p_25 = readmatrix("K_P_25.csv");

UR_Data_K_p_1_5 = readmatrix("UR10_1_data_1_5.txt");
UR_Data_K_p_2 = readmatrix("UR10_1_data_2.txt");
UR_Data_K_p_3 = readmatrix("UR10_1_data_3.txt");
UR_Data_K_p_5 = readmatrix("UR10_1_data_5.txt");
UR_Data_K_p_10 = readmatrix("UR10_1_data_10.txt");
UR_Data_K_p_25 = readmatrix("UR10_1_data_25.txt");

t = linspace(0,1000,10001);
```

TRIM DATASETS

```
Control(1:178,:) = [];
Control(127:length(Control),:) = [];
K_p_1(1:254,:) = [];
K_p_1(112:length(K_p_1),:) = [];
K_p_1_5(1:140,:) = [];
K_p_1_5(62:length(K_p_1_5),:) = [];
K_p_2(1:95,:) = [];
K_p_2(162:length(K_p_2),:) = [];
K_p_3(1:220,:) = [];
K_p_3(97:length(K_p_3),:) = [];
K_p_5(1:223,:) = [];
K_p_5(85:length(K_p_5),:) = [];
K_p_10(1:207,:) = [];
K_p_10(142:length(K_p_10),:) = [];
K_p_25(1:180,:) = [];
K_p_25(145:length(K_p_25),:) = [];

Control(:,2) = Control(:,2) - Control(5,2);
K_p_1_5(:,2) = K_p_1_5(:,2) - K_p_1_5(10,2);
K_p_2(:,2) = K_p_2(:,2) - K_p_2(1,2);
K_p_3(:,2) = K_p_3(:,2) - K_p_3(5,2);
K_p_5(:,2) = K_p_5(:,2) - K_p_5(1,2);
K_p_10(:,2) = K_p_10(:,2) - K_p_10(5,2);
K_p_25(:,2) = K_p_25(:,2) - K_p_25(5,2);

UR_Data_K_p_1_5(1:78,:) = [];
UR_Data_K_p_2(1:73,:) = [];
UR_Data_K_p_3(1:93,:) = [];
UR_Data_K_p_5(1:54,:) = [];
UR_Data_K_p_10(1:85,:) = [];
UR_Data_K_p_25(1:124,:) = [];

UR_Data_K_p_1_5(:,1) = UR_Data_K_p_1_5(:,1) - UR_Data_K_p_1_5(1,1);
```

```
UR_Data_K_p_2(:,1) = UR_Data_K_p_2(:,1) - UR_Data_K_p_2(1,1);
UR_Data_K_p_3(:,1) = UR_Data_K_p_3(:,1) - UR_Data_K_p_3(1,1);
UR_Data_K_p_5(:,1) = UR_Data_K_p_5(:,1) - UR_Data_K_p_5(1,1);
UR_Data_K_p_10(:,1) = UR_Data_K_p_10(:,1) - UR_Data_K_p_10(1,1);
UR_Data_K_p_25(:,1) = UR_Data_K_p_25(:,1) - UR_Data_K_p_25(1,1);
```

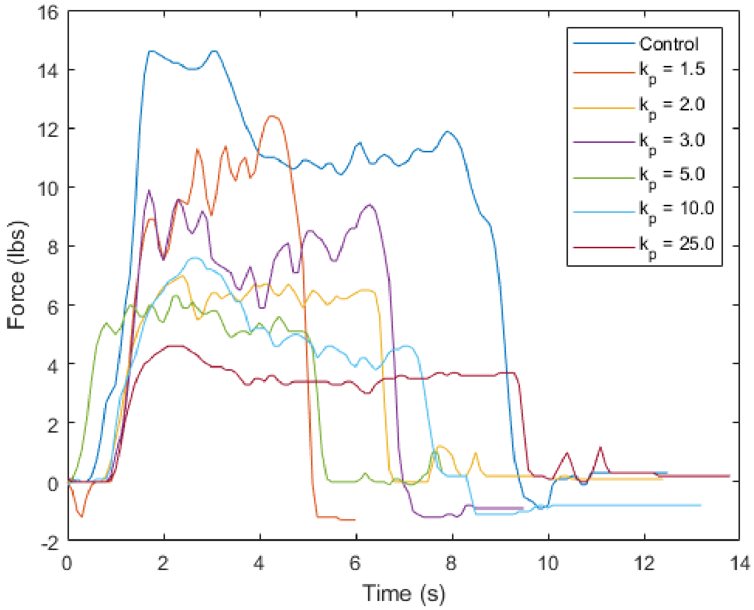
CALCULATE DATA

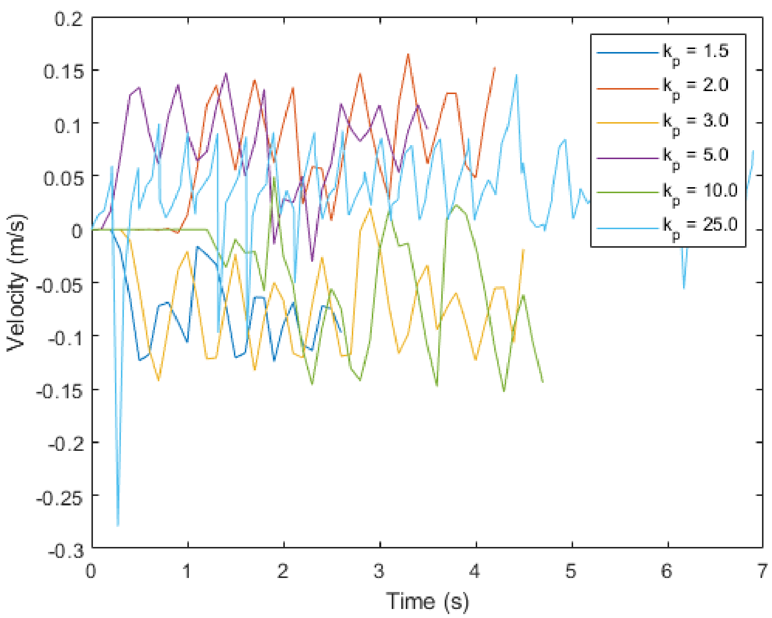
```
%FROM Data - Velocities of MANTIS
v_Control = 0.125; %m/s
v_K_p_1_5 = 0.084; %m/s
v_K_p_2 = 0.133; %m/s
v_K_p_3 = 0.121; %m/s
v_K_p_5 = 0.136; %m/s
v_K_p_10 = 0.145; %m/s
v_K_p_25 = 0.085; %m/s (possibly 0.145 m/s)
lb_N = 4.44822;

P_Control = lb_N*v_Control*Control(:,2);
P_K_p_1_5 = lb_N*v_K_p_1_5*K_p_1_5(:,2);
P_K_p_2 = lb_N*v_K_p_2*K_p_2(:,2);
P_K_p_3 = lb_N*v_K_p_3*K_p_3(:,2);
P_K_p_5 = lb_N*v_K_p_5*K_p_5(:,2);
P_K_p_10 = lb_N*v_K_p_10*K_p_10(:,2);
P_K_p_25 = lb_N*v_K_p_25*K_p_25(:,2);

for i = 10:length(P_K_p_10)
    if rem(i,2) == 0
        P_K_p_10(i) = [];
    end
    if i >= length(P_K_p_10)
        break
    end
end

for i = 10:length(P_K_p_25)
    if rem(i,2) == 0
        P_K_p_25(i) = [];
    end
    if i >= length(P_K_p_25)
        break
    end
end
for i = 10:length(P_K_p_25)
    if rem(i,2) == 0
        P_K_p_25(i) = [];
    end
    if i >= length(P_K_p_25)
        break
    end
end
P_K_p_25(35:38) = [];
```

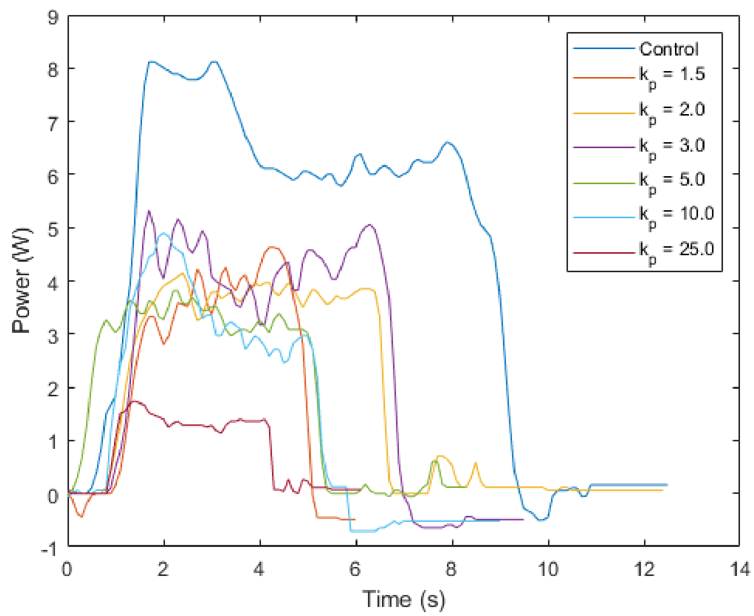
PLOT RAW DATA OVER EACHOTHER

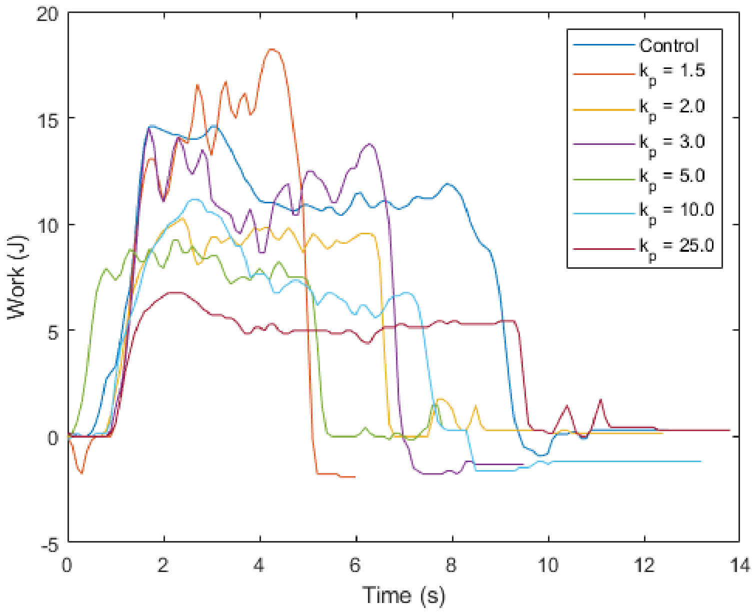
```
figure(1)
plot(t(1:length(Control)),Control(:,2));
hold on
%plot(t(1:length(K_p_1)),K_p_1(:,2));
%hold on
plot(t(1:length(K_p_1_5)),K_p_1_5(:,2));
hold on
plot(t(1:length(K_p_2)),K_p_2(:,2));
hold on
plot(t(1:length(K_p_3)),K_p_3(:,2));
hold on
plot(t(1:length(K_p_5)),K_p_5(:,2));
hold on
plot(t(1:length(K_p_10)),K_p_10(:,2));
hold on
plot(t(1:length(K_p_25)),K_p_25(:,2));
legend("Control","k_p = 1.5","k_p = 2.0","k_p = 3.0","k_p = 5.0","k_p = 10.0","k_p = 25.0");
xlabel("Time (s)");
ylabel("Force (lbs)");

figure(2)
```

```
plot(UR_Data_K_p_1_5(:,1),UR_Data_K_p_1_5(:,19));
hold on
plot(UR_Data_K_p_2(:,1),UR_Data_K_p_2(:,19));
hold on
plot(UR_Data_K_p_3(:,1),UR_Data_K_p_3(:,19));
hold on
plot(UR_Data_K_p_5(:,1),UR_Data_K_p_5(:,19));
hold on
plot(UR_Data_K_p_10(:,1),UR_Data_K_p_10(:,19));
hold on
plot(UR_Data_K_p_25(:,1),UR_Data_K_p_25(:,19));
legend("k_p = 1.5","k_p = 2.0","k_p = 3.0","k_p = 5.0","k_p = 10.0","k_p = 25.0");
xlabel("Time (s)");
ylabel("Velocity (m/s)");

figure(3)
plot(t(1:length(P_Control)),P_Control);
hold on
plot(t(1:length(P_K_p_1_5)),P_K_p_1_5);
hold on
plot(t(1:length(P_K_p_2)),P_K_p_2);
hold on
plot(t(1:length(P_K_p_3)),P_K_p_3);
hold on
plot(t(1:length(P_K_p_5)),P_K_p_5);
hold on
plot(t(1:length(P_K_p_10)),P_K_p_10);
hold on
plot(t(1:length(P_K_p_25)),P_K_p_25);
legend("Control","k_p = 1.5","k_p = 2.0","k_p = 3.0","k_p = 5.0","k_p = 10.0","k_p = 25.0");
xlabel("Time (s)");
ylabel("Power (W)");

figure(4)
plot(t(1:length(Control)),Control(:,2));
hold on
plot(t(1:length(K_p_1_5)),.33*lb_N*K_p_1_5(:,2));
hold on
plot(t(1:length(K_p_2)),.33*lb_N*K_p_2(:,2));
hold on
plot(t(1:length(K_p_3)),.33*lb_N*K_p_3(:,2));
hold on
plot(t(1:length(K_p_5)),.33*lb_N*K_p_5(:,2));
hold on
plot(t(1:length(K_p_10)),.33*lb_N*K_p_10(:,2));
hold on
plot(t(1:length(K_p_25)),.33*lb_N*K_p_25(:,2));
legend("Control","k_p = 1.5","k_p = 2.0","k_p = 3.0","k_p = 5.0","k_p = 10.0","k_p = 25.0");
xlabel("Time (s)");
ylabel("Work (J)");
```


Force (lbs)
Time (s)
Control
k_p = 1.5
k_p = 2.0
k_p = 3.0
k_p = 5.0
k_p = 10.0
k_p = 25.0

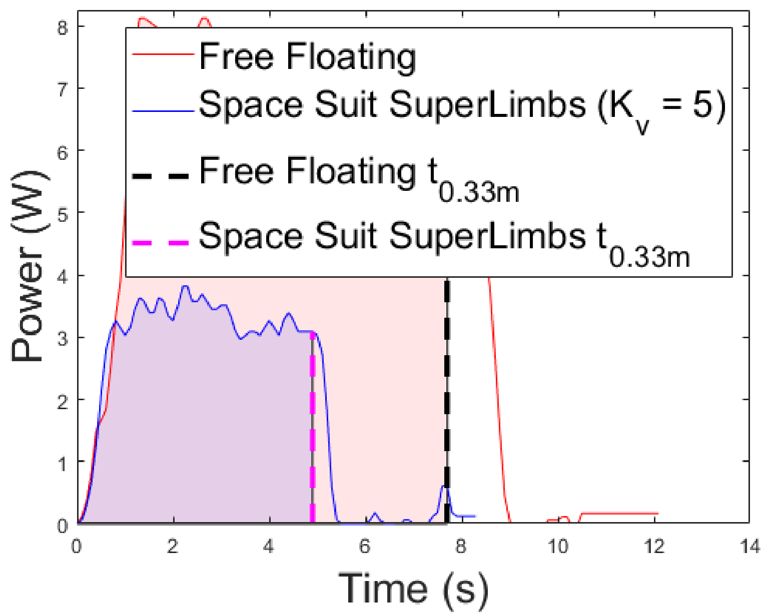

Velocity (m/s)
Time (s)
k_p = 1.5
k_p = 2.0
k_p = 3.0
k_p = 5.0
k_p = 10.0
k_p = 25.0





PLOT FINAL DATA

```
figure(5)
X1 = [t(1) t(1:78) t(78)];
Y1 = [0 transpose(P_Control(5:82)) 0];
X2 = [t(1) t(1:50) t(50)];
Y2 = [0 transpose(P_K_p_5(1:50)) 0];
fill(X1,Y1,'r','FaceAlpha',0.1);
hold on
fill(X2,Y2,'b','FaceAlpha',0.1);
hold on
plot(t(1:length(P_Control)-4),P_Control(5:length(P_Control)),'color','r');
hold on
plot(t(1:length(P_K_p_5)),P_K_p_5,'color','b');
hold on
plot([t(78) t(78)],[0 P_Control(78)],'linestyle','--','linewidth',2.5,'color','k');
hold on
plot([t(50) t(50)],[0 P_K_p_5(50)],'linestyle','--','linewidth',2.5,'color','m');
legend("","","Free Floating","Space Suit SuperLimbs (K_v = 5)","Free Floating t_{0.33m}","Space Suit SuperLimbs t_{0.33m}", 'FontSize', 18);
xlabel("Time (s)", 'FontSize', 20); ylabel("Power (W)", 'FontSize', 20);
ylim([0 8.25]);
```

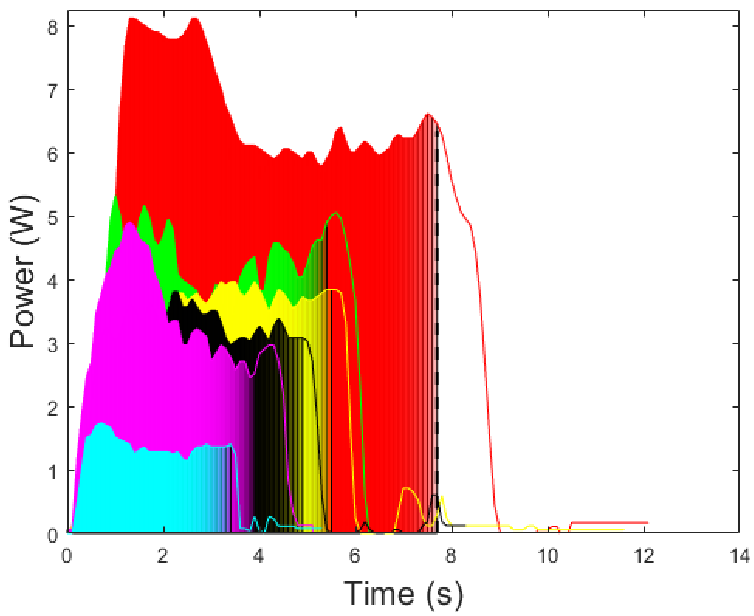


ANIMATE FINAL DATA

```
figure(6)
pause(10);
for i = 1:78
X1 = [t(1) t(1:i) t(i)];
Y1 = [0 transpose(P_Control(5:4+i)) 0];
fill(X1,Y1,'r','FaceAlpha',0.3);
hold on
plot(t(1:i),P_Control(5:4+i),'color','r');
xlim([0 14]);
ylim([0 8.25]);
%legend("","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
F = getframe(gcf);
pause(0.1);
end
hold on
plot([t(78) t(78)],[0 P_Control(78)],'linestyle','--','linewidth',1.5,'color','k');
xlim([0 14]);
ylim([0 8.25]);
%legend("","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
F = getframe(gcf);
for i = 78:length(P_Control)-4
plot(t(1:i),P_Control(5:i+4),'color','r');
xlim([0 14]);
ylim([0 8.25]);
%legend("","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
F = getframe(gcf);
pause(0.1);
end
pause(1);
F = getframe(gcf);

for i = 1:55
X1 = [t(1) t(1:i) t(i)];
Y1 = [0 transpose(P_K_p_3(8:7+i)) 0];
fill(X1,Y1,'g','FaceAlpha',0.3);
hold on
plot(t(1:i),P_K_p_3(8:7+i),'color','g');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
hold on
plot([t(55) t(55)],[0 K_p_3(55)],'linestyle','--','linewidth',1.5,'color','k');
```

```
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
F = getframe(gcf);
for i = 55:length(P_K_p_3)-8
plot(t(1:i),P_K_p_3(8:i+7),'color','g');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
pause(1);
F = getframe(gcf);

for i = 1:56
X1 = [t(1) t(1:i) t(i)];
Y1 = [0 transpose(P_K_p_2(8:7+i)) 0];
fill(X1,Y1,'y','FaceAlpha',0.3);
hold on
plot(t(1:i),P_K_p_2(8:7+i),'color','y');
xlim([0 14]);
ylim([0 8.25]);
%legend("","Free Floating", 'K_v = 2', 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
hold on
plot([t(56) t(56)],[0 K_p_2(56)],'linestyle','--','linewidth',1.5,'color','k');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating","","", 'K_v = 2','FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
F = getframe(gcf);
for i = 56:length(P_K_p_2)-8
plot(t(1:i),P_K_p_2(8:i+7),'color','y');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating","","",'K_v = 2', 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
pause(1);
F = getframe(gcf);

for i = 1:50
X2 = [t(1) t(1:i) t(i)];
Y2 = [0 transpose(P_K_p_5(1:i)) 0];
fill(X2,Y2,'k','FaceAlpha',0.3);
hold on
plot(t(1:i),P_K_p_5(i),'color','k');
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
hold on
%plot([t(50) t(50)],[0 P_K_p_5(50)],'linestyle','--','linewidth',1.5,'color','k');
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
F = getframe(gcf);
for i = 50:length(P_K_p_5)
plot(t(1:i),P_K_p_5(1:i),'color','k');
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
pause(1);
F = getframe(gcf);

for i = 1:40
X1 = [t(1) t(1:i) t(i)];
Y1 = [0 transpose(P_K_p_10(8:7+i)) 0];
fill(X1,Y1,'m','FaceAlpha',0.3);
```

```
hold on
plot(t(1:i),P_K_p_10(8:7+i),'color','m');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
hold on
plot([t(40) t(40)],[0 K_p_10(40)],'linestyle','--','linewidth',1.5,'color','k');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
F = getframe(gcf);
for i = 40:length(P_K_p_10)-8
plot(t(1:i),P_K_p_10(8:i+7),'color','m');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
pause(1);
F = getframe(gcf);

for i = 1:35
X1 = [t(1) t(1:i) t(i)];
Y1 = [0 transpose(P_K_p_25(8:7+i)) 0];
fill(X1,Y1,'c','FaceAlpha',0.3);
hold on
plot(t(1:i),P_K_p_25(8:7+i),'color','c');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
hold on
plot([t(35) t(35)],[0 K_p_25(35)],'linestyle','--','linewidth',1.5,'color','k');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
F = getframe(gcf);
for i = 35:length(P_K_p_25)-8
plot(t(1:i),P_K_p_25(8:i+7),'color','c');
xlim([0 14]);
ylim([0 8.25]);
%legend("","","Free Floating", 'FontSize', 16);
xlabel("Time (s)", 'FontSize', 16); ylabel("Power (W)", 'FontSize', 16);
pause(0.1);
F = getframe(gcf);
end
pause(1);
F = getframe(gcf);
```



Write Video File

video = VideoWriter('test.avi'); video.FrameRate = 60; open(video) writeVideo(video,F); close(video);

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