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**Title:** Inverse Dynamics Analysis for Squat Exercise on a Human Centrifuge

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# **Inverse Dynamics Analysis for Squat Exercise on a Human Centrifuge**

by

**Punyapat Saksupapchon**

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on 29 April 2016

## **ABSTRACT**

This study is a part of the ExRoTe study (Exercise Performance with the Body Mass Accelerated by Rotation Compared with the Acceleration by the Terrestrial Gravitational Field) at the Institute of Aerospace Medicine, German Aerospace Center (DLR). As squat is a resistive exercise that has significant musculoskeletal and cardiovascular benefits when combined with artificial gravity (AG), it is a potential countermeasure to the physiological deconditioning that results from long-duration spaceflight. However, body movements on a rotating short-arm human centrifuge are affected by the gravity gradient and Coriolis accelerations. The biomechanical responses including leg kinematics, foot reaction forces, joint torques, and muscle activities of squat exercise while lying supine on a human centrifuge were investigated and compared with 1-G upright squats on Earth. The purpose of this study is to develop the biomechanical model and simulation for squat exercise on a short-radius human centrifuge for predicting foot reaction forces, the effects of the Coriolis accelerations and gravity gradient acting on the body during the exercise, and estimating joint torques in order to provide safe and effective artificial gravity squat exercise protocols for future human missions to distant destinations such as the Moon and Mars. In order to validate the model and simulation, the human measurements and squat experiments were conducted on the next generation DLR Short-Arm Human Centrifuge (envifuge) and on the ground control station to collect the data of 8 subjects (4 males and 4 females). All of the subjects were healthy at age between 20 and 50 years, height between 1.58 and 1.90 meters, weight between 50 and 100 kilograms, and BMI between 18 and 28. Motion capturing system, force plates and accelerometers were the main equipment used for collecting the data. This research furthered our understanding of the behavior of the musculoskeletal system in an artificial gravity environment, human kinematics and dynamics, and the effects of the Coriolis accelerations and gravity gradient acting on the body during the artificial gravity squat exercise. For the next generation DLR Short-Arm Human Centrifuge (envifuge), it was the first time that the basic vital parameters in this context were observed and recorded. Furthermore, using inverse dynamics method to develop a biomechanical model and simulation for artificial gravity squat exercise that demonstrate foot reaction forces, joint torques, and body movements and deflections due to the Coriolis effect and g-gradient with the adjustable input parameters including radius of the centrifuge, rotation rate, and test subject's height, weight, and lengths of body parts, was new knowledge and would be very beneficial to the further artificial gravity squat exercise studies as well as other exercises such as hopping, jumping, or cycling along with the studies on cardiovascular system during short-radius centrifugation. Moreover, it may also lead to developing, improving, and standardizing artificial gravity exercise protocols, operations and safety of various centrifuges.

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## **Chapter 1. Introduction**

Artificial gravity (AG) created by short-radius centrifugation is a potential countermeasure to the physiological deconditioning that results from long-duration spaceflight. As space agencies seek to undertake human missions to distant destinations, short-radius artificial gravity might be essential during extended sojourns in the hypo-gravity environments of many of the celestial objects targeted for exploration, including Moon, Mars, Mars moons, asteroids, and other destinations. In habitat throughout the surface stay, optimal artificial gravity prescriptions for the crews are necessary. AG alone does not ensure fitness; we need to do physical exercise during centrifugation to accomplish a comprehensive countermeasure. Squat is a resistive exercise that has significant musculoskeletal and cardiovascular benefits when combined with artificial gravity. Before artificial gravity exercise can be considered safe and effective, we must understand how Coriolis accelerations and a gravity gradient affect our body movements (biomechanics) and how centrifuge-based exercises differ from Earth-upright ones. This project aims to investigate and develop biomechanical (inverse dynamics) model and simulation for squat exercise on a human centrifuge and collect data of test subjects to compare, analyze, and understand its performance in order to provide safe and effective artificial gravity squat exercise protocols in the future.

## **Chapter 2. Background**

Human space exploration has been limited thus far to low Earth orbit and to short visits to the Moon. For the short-duration missions, the adverse effects of weightlessness on the human body are minimal. However, once we begin extended exploration of the Moon and beyond, mission durations will increase significantly, thus exposing the crews to the detrimental effects of weightlessness. The consequences of long-term weightlessness include undesirable physiological adaptations that impede the ability of astronauts to function efficiently upon the return to an environment with gravity. The more serious of these affects include sensory-motor and cardiovascular deconditioning, orthostatic intolerance, muscular atrophy, and bone demineralization [1].

Artificial gravity has the potential to fully mitigate the physiological deconditioning that results from long-term exposure to weightlessness. It could replace terrestrial gravity with inertial forces generated by centrifugation or sustained linear acceleration. However, there remain many unknowns as to how humans can adapt to a rotating environment and then re-adapt to a non-rotating environment. Recent studies suggest that humans can adapt to high rates of rotation at short radius. Therefore, an alternative to rotating the entire habitat is to provide a

short-radius centrifuge within the habitat and deliver therapeutic doses of artificial gravity. This would result in an overall simpler and more affordable design [1].

With mass  $m$ , radius  $r$ , and angular velocity  $\omega$ , the magnitude of the centripetal force of circular motion is  $F = m\omega^2 r$ . The magnitude of the centripetal acceleration, which is referred to as the gravity level, is  $a = \omega^2 r$ , and is always directed radially outward from the center of the rotating body. For a given rotation rate, the gravity level (g-level) varies along the radius. It turns out that to generate 1-g artificial gravity, the radius needs to be very large with a slow rotation rate (e.g. 35 m for 5 rpm), or very small with a fast rotation rate (e.g. 4 m for 15 rpm)[1].

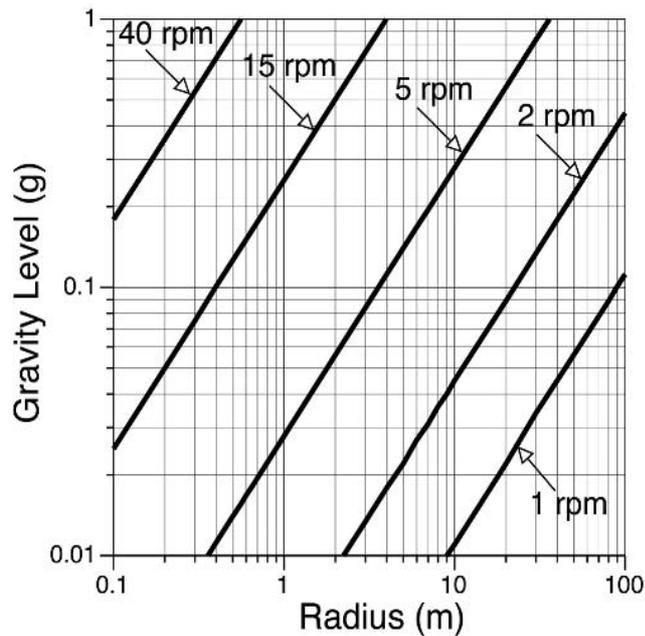


Figure 1. Gravity level generated during centrifugation as a function of radius for four given rotation rates [1]

For an astronaut of height  $h$ , lying in a centrifuge along a radius with his feet positioned at the rim and his head pointing towards the center of rotation, his head has a radius of rotation equal to  $r - h$ . The ratio of head acceleration to foot acceleration can be simply expressed as

$$a_{\text{head}}/a_{\text{foot}} = \omega^2 (r - h) / \omega^2 r = (r - h) / r$$

By way of example, for an astronaut of height  $h = 2$  m in a rotating environment with a radius of 100 m, this ratio is 98%, which corresponds to a gravity gradient of 2%. An individual would not likely perceive a difference of only 2%. However, for radii of rotation less than 10 m, the ratio is from 80% to 0% that corresponds to the gravity gradient ranges from 20% to 100%, which may be perceived as a bent posture [1].

The Coriolis acceleration is a direct result of any linear movement within the rotating reference frame and is equal to twice the cross product of the angular velocity vector  $\omega$  and the linear velocity vector  $v$  of the moving object, person, or body part. The Coriolis acceleration

acts in a direction that is perpendicular both to the direction of the velocity of the moving subject mass and to the axis of rotation. The magnitude of the Coriolis force is  $F = 2m \omega v$ . It is important to note that the Coriolis force is independent of the radius of centrifugation. That is, its magnitude is the same at all distances from the center of rotation [1].

The characteristics of the Coriolis force or acceleration [1]:

- When the velocity  $v$  is zero, the Coriolis acceleration is zero.
- When  $v$  is parallel to the rotation axis, the Coriolis acceleration is zero.
- When  $v$  is directed radially inward (outward) towards (away from) the axis of rotation, the resulting Coriolis acceleration is aligned with (opposed to) the direction of rotation (parallel to the tangential velocity).
- If  $v$  is aligned with (opposed to) the direction the rotation (parallel to the tangential velocity), the Coriolis acceleration acts radially outward from (toward) the axis of rotation.

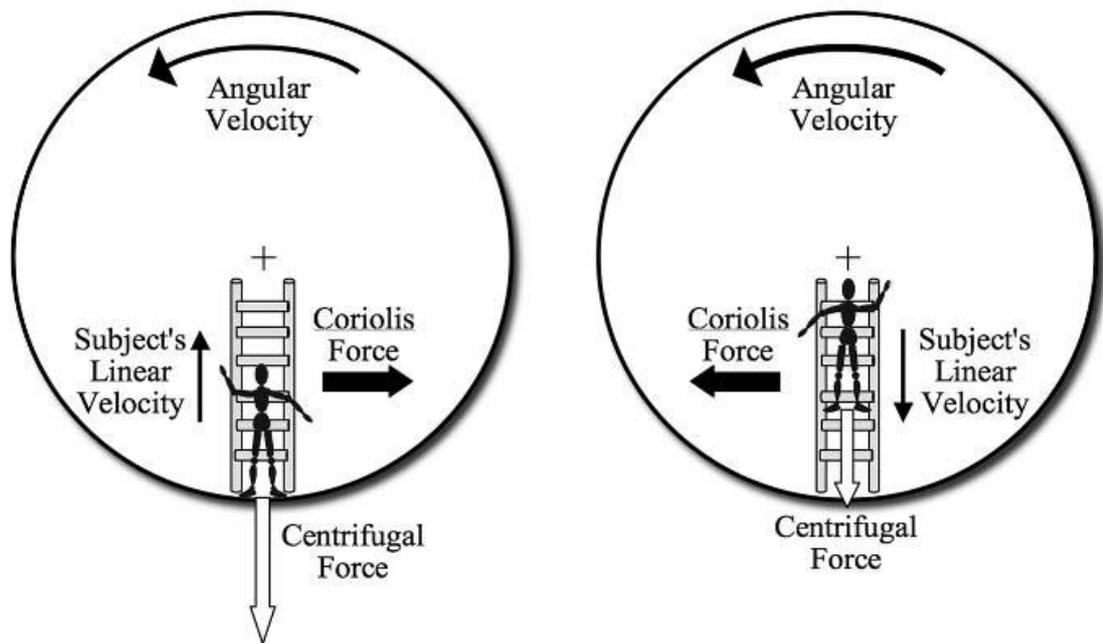


Figure 2. Coriolis and centrifugal forces exerted on a passenger climbing a ladder up (left) or down (right) in a rotating environment. The Coriolis force has the same amplitude in both conditions, but its direction is reversed. Note that the magnitude of the centrifugal force is greater when the space traveler is at the bottom of the ladder, due to the increased distance from the axis of rotation [1].

It is notable that during the first few reaches in the rotating environment, the subjects felt the Coriolis forces deviating their arm. Interestingly, after multiple reaches, test subjects no longer perceived the Coriolis force, and the movements seemed completely normal. After adaptation to the rotating environment, limb movement feels completely natural and indistinguishable from the normal non-rotating environment (DiZio and Lackner 1995) [1].

## Chapter 3. Definitions

- **Artificial gravity (AG)** is the simulation of gravitational forces aboard a space vehicle that is in orbit (free fall) or in transit to another planet. It can refer to a spinning spacecraft or a centrifuge within the spacecraft such that a gravity-like force results [1].
- **Gravity gradient (g-gradient)** is the variation in artificial gravity level as a function of distance from the center of rotation [1].
- **The Coriolis effect** is the apparent deflection of a moving object in a rotating frame of reference [1].
- **Short-radius centrifuge** is a device where the subject is immobile, i.e., either strapped in or otherwise constrained [1]. Although there is no clear distinction about the radius of short-radius centrifuge and long-radius centrifuge, most people would probably see 10 m as a useful limit.
- **Long-radius centrifuge** is a device that a subject is completely free to move about [1].
- **Mechanics** is the branch of physics that studies the motion of objects and the forces that cause that motion [10].
- **Rigid-body mechanics** is an area in biomechanics, in which the object being analyzed is assumed to be rigid and the deformations in its shape are so small that they can be ignored. This assumption is quite reasonable for most biomechanical studies of the major segments of the body. It saves considerable mathematical and modeling work without great loss of accuracy. Rigid-body mechanics is divided into statics and dynamics [10].
- **Statics** is the study of objects at rest or in uniform (constant) motion [10].
- **Dynamics** is the study of objects being accelerated by the actions of forces, which is divided into two branches: kinematics and kinetics [10].
- **Kinematics** is motion description, usually measured in linear (meters, feet, etc.) or angular (radians, degrees, etc.) terms. Examples of the kinematics of running could be the speed of the athlete, the length of the stride, or the angular velocity of hip extension [10].
- **Kinetics** is concerned with determining the causes of motion. Examples of kinetic variables in running are the forces between the feet and the ground or the forces of air resistance. Kinetic information is often more powerful in improving human motion because the causes of poor performance have been identified [10].
- **Inverse dynamics** is the work backward from kinematics to the resultant kinetics [10].
- **Direct dynamics** is calculating the motion from the input “what-if” kinetics and body configurations [10].
- **Biomechanical modeling** involves the development of a mathematical representation of the biomechanical system [10].
- **Biomechanical simulation** uses biomechanical models to examine how changes in various techniques and parameters affect the movement or body [10].

## **Chapter 4. Problem Statement**

According to the existing studies on squat exercise during short-radius centrifugation, there is still no biomechanical model and simulation that demonstrate foot reaction forces and body forces (that might trigger movements) due to the Coriolis effect and g-gradient with different human parameters such as height, weight, and length of each concerned body part given the attributes of the short-radius centrifuge setting. If we can understand, develop, and validate the biomechanical model and simulation of the AG squat exercise, this study will be very beneficial for the future studies on other exercises (e.g. hopping, jumping, or cycling) along with the studies on cardiovascular system during short-radius centrifugation. It may lead to developing, improving, or standardize the artificial gravity exercise protocol and the operational and safety issues for various centrifuges.

## **Chapter 5. Objectives**

1. To investigate biomechanical responses (leg kinematics, foot reaction forces, and muscle activity) to squat exercise while lying supine on a human centrifuge comparing with Earth upright squats
2. To develop a biomechanical model and stimulation of squat exercise on a short-radius human centrifuge for predicting foot reaction forces and the effects of the Coriolis accelerations, and gravity gradient acting on the body during the exercise and estimating joint torques and repetitive motion injury risk.
3. To validate the model and simulation by human experiments and measurements during AG squat on the next generation DLR Short-Arm Human Centrifuge (envifuge)
4. To develop a safe and optimal artificial gravity squat exercise protocol

## **Chapter 6. Potential Impacts**

This study will help us gain a better understanding on how AG squat exercise could be an effective countermeasure to the physiological deconditioning that results from long-duration spaceflight, human kinematics and dynamics during AG squat exercise, and the effects of the Coriolis accelerations, gravity level and gravity gradient acting on the body during AG squat exercises. Moreover, the results of this study will include the biomechanical model and simulation for AG squat exercise, which will be very beneficial for the future studies on other exercises (e.g. hopping, jumping, or cycling) along with the studies on cardiovascular system during short-radius centrifugation. It may lead to developing, improving, or standardize the artificial gravity exercise protocol and the operational and safety issues for various centrifuges.

## Chapter 7. Literature Review

Current countermeasures on the International Space Station (ISS), such as resistive exercise on the Advanced Resistive Exercise Device (ARED), treadmill running, and cycling, have only proven to be partially beneficial. In particular, astronauts returning from six months aboard the ISS have shown that anti-gravity muscle volume and peak power still decrease significantly versus preflight (-13% and -32%, respectively) [7]. Bone mineral density (BMD) and strength losses also persist in the lower extremities with integral hip BMD being lost at an average of 1.5% per month [8, 9].

Artificial gravity (AG) has long been suggested as a comprehensive countermeasure that is capable of challenging all the physiological systems at the same time, therefore maintaining overall health during extended weightlessness [11]. Three studies of the former MIT Aero-Astro PhD students show that couple AG with squats, stair steppers, or ergometer is effective in preventing cardiovascular and musculoskeletal deconditioning and demonstrate the feasibility of conducting these exercises in a rotating environment [2, 3, 4, 11]. Stepping in place significantly reduced the physiological responses to increasing g-level and g-gradient, suggesting that subjects may be able to better tolerate exposure to high-g centrifugation if they exercise. Further, an eight-week exercise program using a stair-stepper on a short-radius centrifuge resulted in improvements to aerobic capacity, strength, and body composition [3].

The study of Duda shows that mediolateral knee travel during the AG squats was 1.0 to 2.0 centimeters greater than Earth-upright squats. Increasing the rotation rate or adding resistive force did not affect the results. The peak foot forces increased with rotation rate, but rarely exceeded 200% body weight. The ratio of left-to-right foot force during centrifugation was non-constant and approximately sinusoidal, suggesting a postural correction for the Coriolis accelerations [2]. The Coriolis accelerations affect the performance both directly, by deflecting the knees medially and laterally and inducing frontal plane joint torques when exercising supine, and indirectly by creating illusions of body tilt that are reflected in the foot forces. Duda further suggested that spinning the centrifuge slower (23 RPM or less), choosing an appropriate body orientation, foot position (elevating the feet above the torso) and foot external rotation, or changing the direction of the Coriolis acceleration vector by putting the subject on their side could reduce or eliminate the effects of these Coriolis accelerations. Besides, the centrifuge would have to be spun in both directions to balance the muscular and skeletal consequences of asymmetric foot loading. Furthermore, there was a qualitative difference in the foot force vs. knee angle profile between upright and centrifuge-supine because of the centripetal acceleration. Muscle activity during AG squats, on the other hand, was often surprisingly similar to upright

over several rotation rates and levels of resistance. It was even possible to match the muscle activity over a large number of knee angles within a set of conditions, unlike the foot reaction forces. [2]

Moreover, Duda developed a two-dimensional mathematical model of the leg press biomechanics (as shown in Figure3) to predict the magnitude and direction of these Coriolis accelerations and foot reaction forces while exercising in artificial gravity. The three links are the torso, thigh and shin, with the ankle and knee modeled as hinge joints.

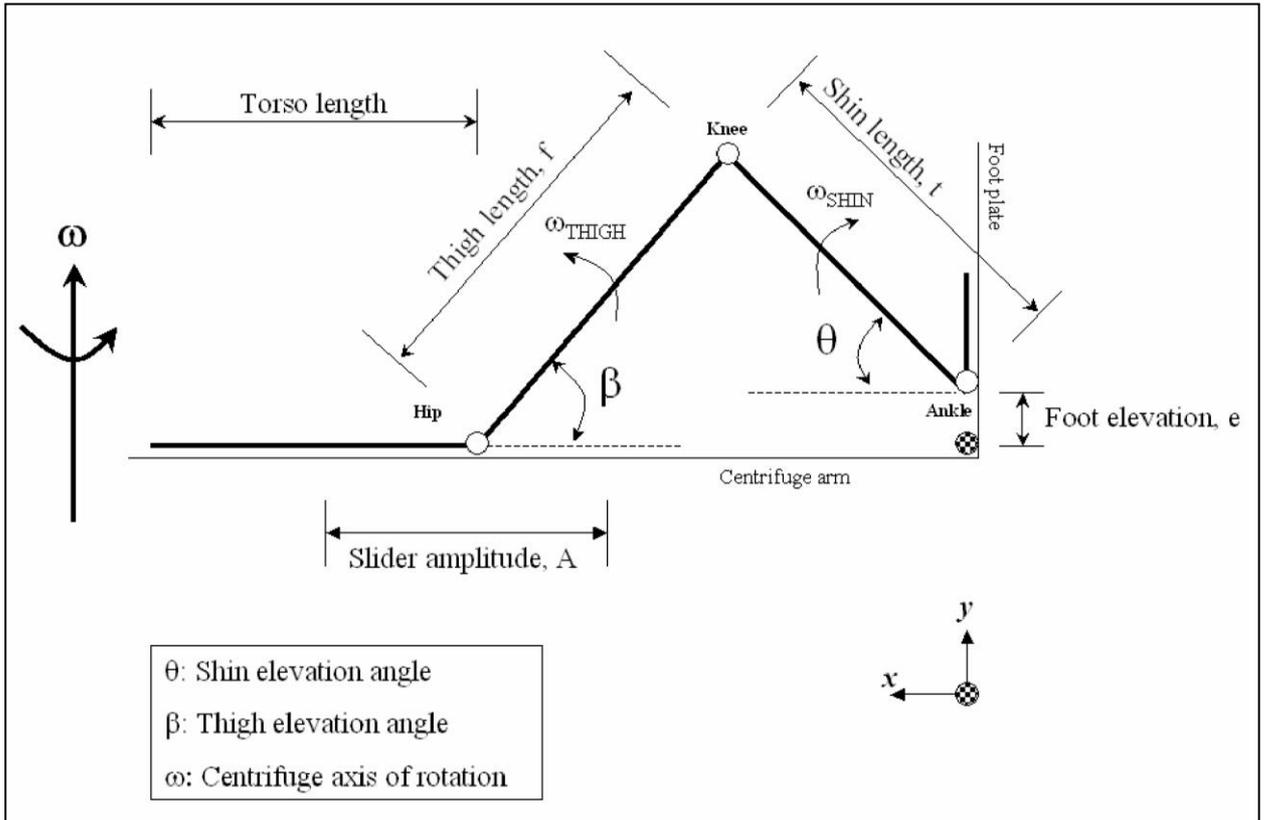


Figure 3. Two-dimensional squat biomechanics diagram with parameters: lengths, angles, and coordinate systems [2]

Coriolis accelerations are defined by the following relationship [2]:

$$\vec{a}_{CORIOLIS} = 2(\vec{\omega}_{CENTRIFUGE} \times \vec{v}_{VELOCITY\_OF\_LIMB})$$

There are two options to manipulate the body orientation and provide the resistive force to the legs: 1) torso motion - fixing the feet and moving the torso along the radius of the centrifuge and 2) foot motion - fixing the torso and allowing the feet to move. Torso motion provides the inertial feel to the squat exercise motions. The lack of this has been cited as possible causes for the ineffectiveness of the iRED in preventing musculoskeletal de-conditioning in ISS astronauts and cosmonauts [2]. On the other hand, the linear movement of the large torso mass

results in Coriolis-induced hip and knee torques in the frontal plane (when supine) and sagittal plane (when shoulder down). Providing sufficient resistive force with foot motion may require tremendous, carefully counterbalanced, mass system or a bungee/spring resistance assembly. However, it would reduce the large Coriolis torques at the hip (knee torques would still exist) [2].

To estimate the foot reaction forces ( $\vec{F}$ ) during supine squats on-board the centrifuge, using Newtonian mechanics, we need to know the mass of the object moving and how fast that object is accelerating:  $\vec{F} = \sum_{i=1}^n m_i \vec{a}_i$ , where  $m_i$  is mass of the  $i^{\text{th}}$  body segment and  $a_i$  is acceleration of the  $i^{\text{th}}$  body segment. The mass remains constant; however, the acceleration is the sum of the centripetal acceleration and acceleration of each  $i^{\text{th}}$  segment itself within the rotating frame:  $a_i = r_{cm,i} \omega_c^2 + a_{cm,i}$ , where  $r_{cm,i}$  is the distance of the  $i^{\text{th}}$  segment center of mass from the axis of rotation,  $\omega_c$  is the centrifuge angular velocity, and  $a_{cm,i}$  is the acceleration of the  $i^{\text{th}}$  segment center of mass relative to the moving centrifuge.

According to the study of Yeadon et al. 1990, the mathematical inertia model of the human body was developed by using cross-section of the stadium solid to calculate volumes of body segments (as shown on figure 4). Each segment is the volume of a truncated pyramid with the bounding stadia that has the same ratio of width to depth. For each segment the mass, location of mass center principal moments of inertia about the mass center and distance between joint centers were calculated by assuming that the solids comprising a segment have coincident longitudinal axes. The values for the left and right limbs are averaged since the simulation model is designed to have symmetrical inertia values. The body segments are sectioned into 40 solids by planes perpendicular to the longitudinal axes of the segments (Figure 5). The levels at which the segments are sectioned are given in Table 1. The inertia model was designed to produce segmental values of an individual for input into the 11-segment simulation model assuming that the segments are rigid bodies and that no movement occurs at the neck, wrists or ankles. The 11 segments of the simulation model comprise the solid listed in Table 2. The density values used in the inertia model were taken from Dempster (1955) and are listed in Table 3 together with the corresponding solids [13]. However, in this model, the head and leg segments are considered as having circular cross-sections of the stadium (t in figure 4 is equal to zero).

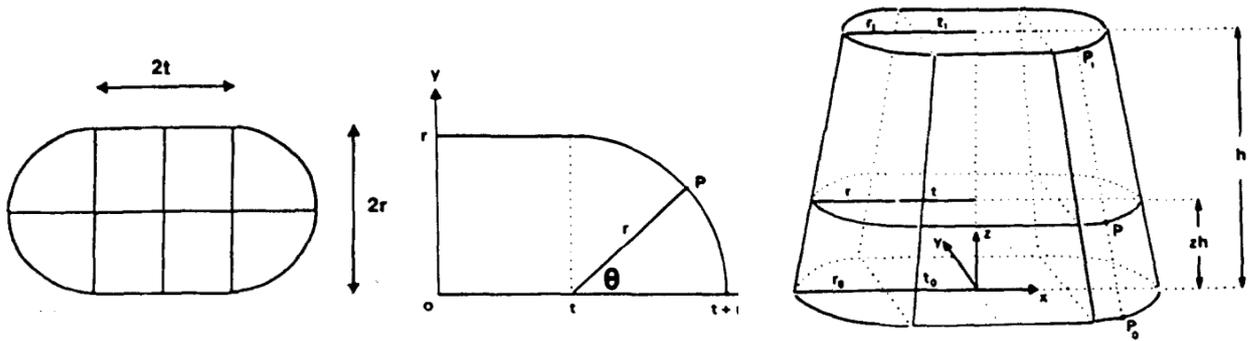


Figure 4. Cross-section of a stadium, a quadrant of the stadium, and a stadium solid [13]  
 (A stadium is a rectangle of width  $2t$  and depth  $2r$  with an adjoining semi-circle at each end of its width.)

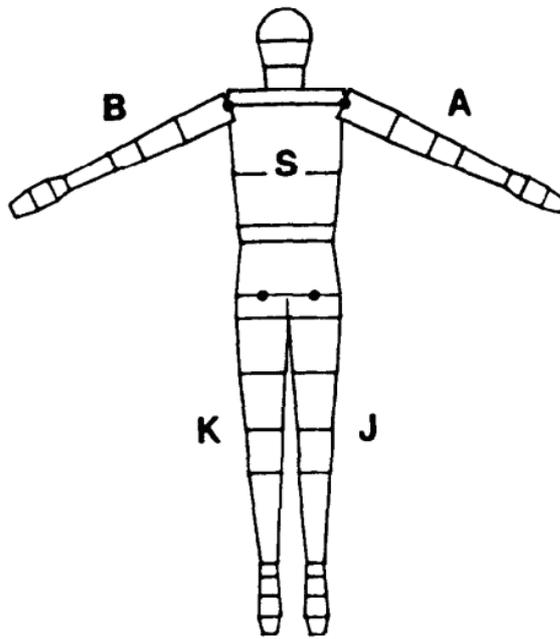


Figure 5. Sectioning of the torso S, left arm A, right arm B, left leg J and right leg K into 40 solids [13]

Table 1. The levels at which the body segments are sectioned [13]

Torso S	Left arm A	Left leg J
Ls0 hip joint center	La0 shoulder joint center	Lj0 hip joint center
Ls1 umbilicus	La1 mid-arm	Lj1 crotch
Ls2 lowest front rib	La2 elbow joint center	Lj2 mid-thigh
Ls3 nipple	La3 maximum forearm perimeter	Lj3 knee joint center
Ls4 shoulder joint center	La4 wrist joint center	Lj4 maximum calf perimeter
Ls5 acromion	La5 base of thumb	Lj5 ankle joint center
Ls6 beneath nose	La6 knuckles	Lj6 heel
Ls7 above ear	La7 fingernails	Lj7 arch
Ls8 top of head		Lj8 ball
		Lj9 toe nails

Table 2. The 11 segments of the simulation model [13]

Segment	Symbol	Solids
Chest-head	C	s4, s5, s6, s7, s8
Thorax	T	s3
Pelvis	P	s1, s2
Left upper arm	A <sub>1</sub>	a1, a2
Left forearm-hand	A <sub>2</sub>	a3, a4, a5, a6, a7
Right upper arm	B <sub>1</sub>	b1, b2
Right forearm-hand	B <sub>2</sub>	b3, b4, b5, b6, b7
Left thigh	J <sub>1</sub>	j1, j2, j3
Left shank-foot	J <sub>2</sub>	j4, j5, j6, j7, j8, j9
Right thigh	K <sub>1</sub>	k1, k2, k3
Right shank-foot	K <sub>2</sub>	k4, k5, k6, k7, k8, k9

Table 3. Segmental density values (Dempster, 1955) [13]

Segment	Solids	Density (kg/L)
Head-neck	s6, s7, s8	1.11
Shoulders	s5	1.04
Thorax	s3, s4	0.92
Abdomen-pelvis	s1, s2	1.01
Upper arm	a1, a2	1.07
Forearm	a3, a4	1.13
Hand	a5, a6, a7	1.16
Thigh	j1, j2, j3	1.05
Lower leg	j4, j5	1.09
Foot	j6, j7, j8, j9	1.10

From the human anthropometric and inertia model developed by Yeadon [13], formulae for the mass  $M$  and location of mass center  $\bar{z}$  derived for a stadium solid are as shown below:

$$M = Dh r_0 [4t_0 F1(a,b) + \pi r_0 F1(a,a)]$$

$$\bar{z} = Dh^2 [4r_0 t_0 F2(a,b) + \pi r_0^2 F2(a,a)] / M$$

When

$D$  = Density of the stadium solid,

$h$  = height of the stadium solid,

$r_0$  = radius of the semi-circle at the lower face stadium,

$r_1$  = radius of the semi-circle at the upper face stadium,

$t_0$  = half width of the rectangle at the lower face stadium,

$t_1$  = half width of the rectangle at the upper face stadium,

$$a = (r_1 - r_0) / r_0$$

$$b = (t_1 - t_0) / t_0$$

The  $r$  and  $t$  can be calculated from input measurements: perimeter ( $p = 4t + 2\pi r$ ) and width ( $w = 2t + 2r$ ) using the equations:  $r = (p - 2w) / (2\pi - 4)$  and  $t = (\pi w - p) / (2\pi - 4)$ .

The functions F1 and F2 are defined by the equations:

$$F1(a,b) = 1 + (a + b)/2 + ab/3$$

$$F2(a,b) = 1/2 + (a + b)/3 + ab/4$$

Yeadon claims that the absolute error in this mass estimation by this model is less than 3%; however, the error may be as high as 5% due to taking the measurements over (snug fitting) clothes and by small changes in measurement location [2].

## Chapter 8. Equipment

### The next generation DLR Short-Arm Human Centrifuge (envifuge)

at the Institute of Aerospace Medicine, German Aerospace Center (DLR), Cologne, Germany



Figure 6. The next generation DLR short-arm human centrifuge (envifuge) [12]

The envifuge has a radius of 380 cm with maximal acceleration of 6g (at 370 cm) and maximal angular velocity of 4 rad/s ( $\approx$  38 rpm). It has the adjustable nacelle for various configuration and positions, which has translation speed of 10 mm/s. The nacelle can handle subjects with a body height from 1.50m to 2.10m and a body weight of 150kg at lateral or supine position. Traveling distance of nacelles for the main arm is 2.5 m and that for the secondary arm is 0.25 - 0.90 m (depending on subject height). There is a lightweight sled available for performing squats and jumps. From the head to the hip, subjects lay on a sled that allows body motion with little friction along the centrifuge radius. The sled position is continuously recorded. At the foot end, there are two triaxial force plates, which measures ground reaction force individually between left and right foot. Instead of the force plate, a vibration plate can be

mounted. Moreover, the Motion Capturing System (MCS) consists of six cameras, which covers almost 50% of the body. This system is mounted on a sled, which can be moved along the lattice arm to position the MCS to capture the movement at the respective region of interest [12].

In this study, the equipment setup on the centrifuge allowed the experiment to have the maximal centrifuge radius of 3.5 m and the minimal centrifuge radius of 2.5 m for all test subjects. The duration of changing the radius was approximately 5-10 minutes, which the test subject could stay on the centrifuge and the motion-capturing camera set would need to be moved to the corrected positions.

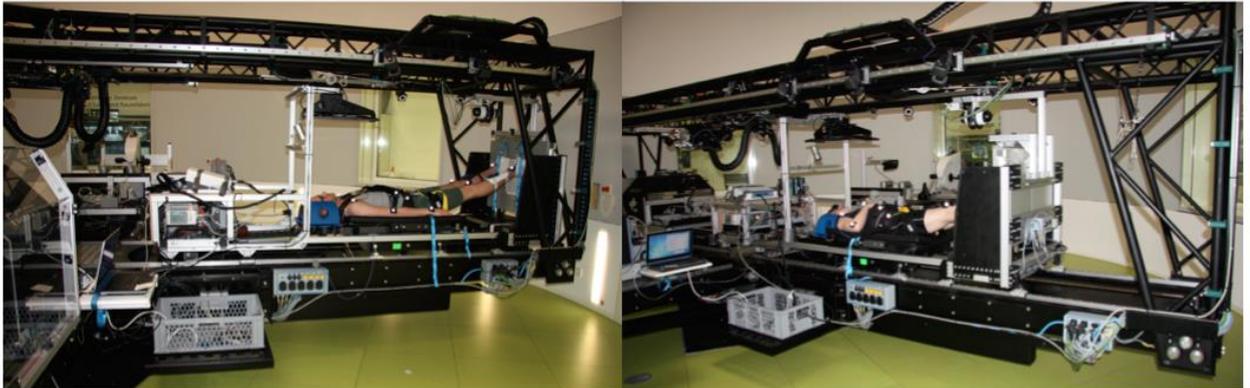


Figure 7. Left is at the maximal radius (3.5m) and right is at the minimal radius (2.5m).

**Equipment on the centrifuge** includes:

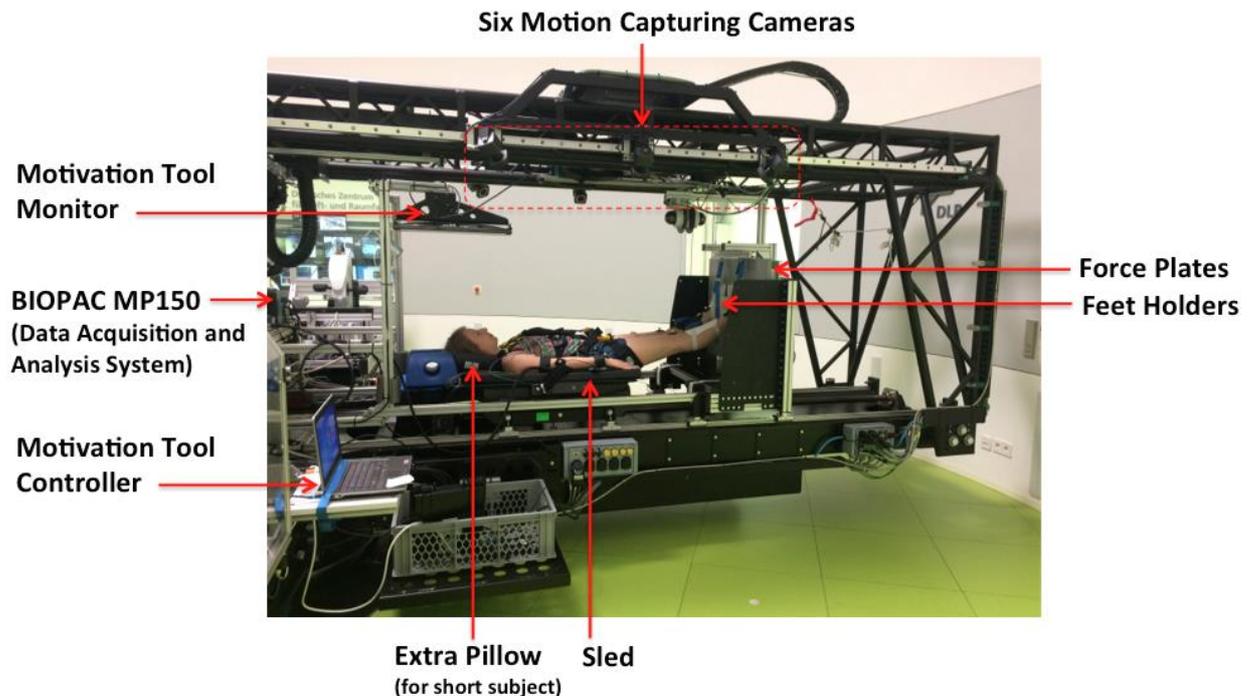


Figure 8. Equipment on the Centrifuge

- Motion Capturing System (Vicon Motion System, Ltd, UK)** consists of six cameras, 14mm-diameter-spherical markers and Vicon Nexus 1.7.2 software, which can also get the analog signals from the sled and the force plates, synchronize and save the data for each individual subject. For each experiment, the cameras were calibrated, set markers origin, and checked if there were reflections. The test subject needed to wear non-reflective clothes. Reflective equipment (rather than the markers) inside the camera range was covered by black stickers or cloth, or masked out from the camera frame on the Vicon Nexus software. Moreover, as shown on figure 14, twelve markers were used to place on test subject's joints including shoulders, hips, knees, ankles, elbows and wrists Besides, one additional marker was placed on the Actibelt equipment. The limitation of the motion capturing system was that the motion capturing files which last longer than 2minutes could not be opened (the software was always collapsed). Thus, in this study, each motion capturing experiment record was shorter than 2 minutes.
- Motivation Tool** provides visual squat exercise guidance to the test subject to follow. The profile signals can be selected or created by the experiment operator. This tool was developed by myself supervised by Dr. Uwe Mittage, at DLR, as the short-term research project titled "Motivation and Guidance Tool for Exercising on the DLR Short-Arm Human Centrifuge (envifuge)" during February 2016. The motivation tool control is run on a laptop attached to a small table rotating with the centrifuge. The control panel requires the experiment operator to set up the maximum and minimum of voltages of the signal from the sled positions, as the moving range of an individual subject is different. During the voltage setup, the shoulders of the test subjects need to be pressed to simulate the centrifugal forces. The signal from the sled is connected to the laptop through BIOPAC MP150 (data acquisition and analysis system) and an analog-digital converter (NI usb multifunction DAQ device), and the signal is also recorded on the Vicon system. In addition, the motivation tool monitor displays a moving white arrow as the profile signal that the test subject needs to follow and a green spot as the real time current sled position of the subject. The profile signal graph can also be seen on top of the screen.

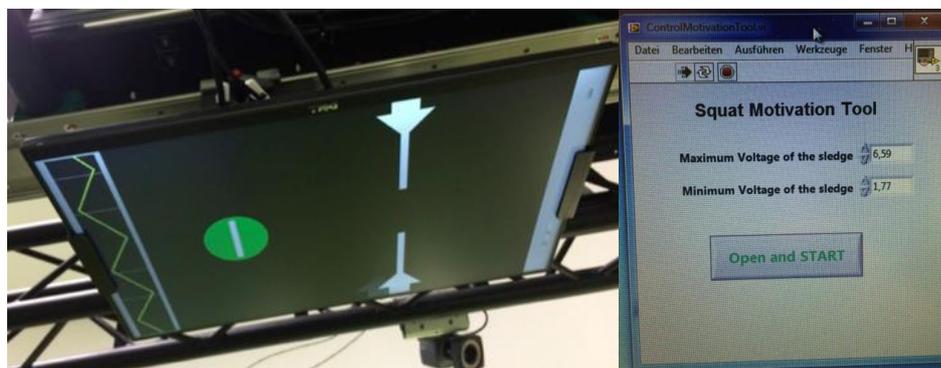


Figure 9. Motivation Tool for Squat Exercise Guidance  
Left is the output monitor. Right is the control panel on the laptop.

- **Force Plates** shows foot reaction forces of left foot and right foot separately. The signals are connected and shown on the Vicon system. The forces consist of three components in x, y, and z directions; however,  $F_y$  and  $F_z$  of the force plates on the centrifuge and on the control station are in different directions as shown on figure 10. Moreover, the weight of each force plate is 15 kg. On the Vicon system of the centrifuge, the forces read from the force plates include their own weight and are quite shaky. In contrast, on the Vicon system of the control station, the forces read from the force plates exclude their own weight and are pretty sharp.

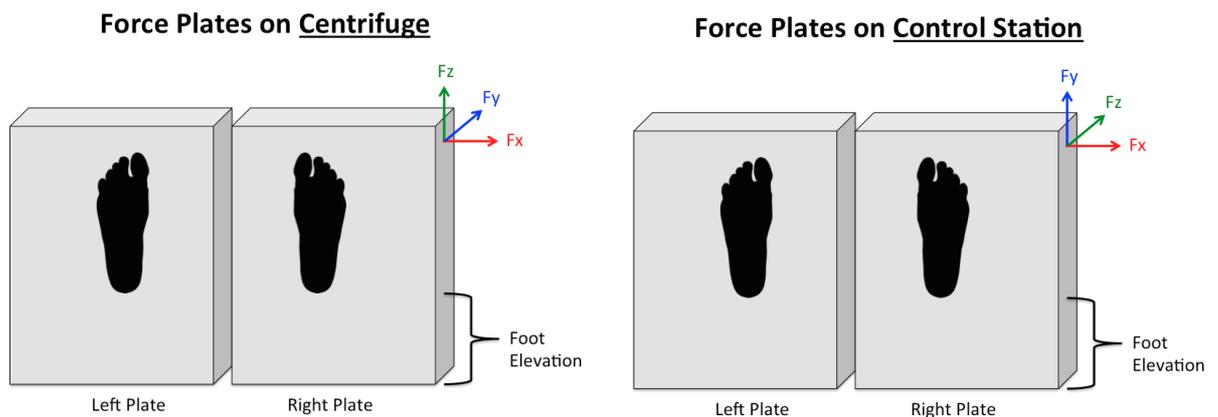


Figure 10. Force Plates. Left is on the centrifuge. Right is on the control station.

- **Feet Holders** hold the test subject's feet apart at 30 cm center-to-center of the feet. The foot elevation level of each subject can be adjusted by adjusting the length of the holder stripes. One foot holder weighs 0.1 kg.



Figure 11. Feet Holders

- Sled on the centrifuge** weighs 14 kg. It is composed of metal structure underneath the body cushion and the head holder. The dimension and center of mass of the sled is shown on figure 12. Most of the test subjects lay on the sled at the acromion level just below the head holder. However, some short subjects need an extra pillow (as shown on figure 13) in order to place the hip lower to prevent the case that, during squatting down, the bottom of the sled hits the bumper at the edge, which leads to wrong forces on the force plates. The width of the extra pillow is 18cm.

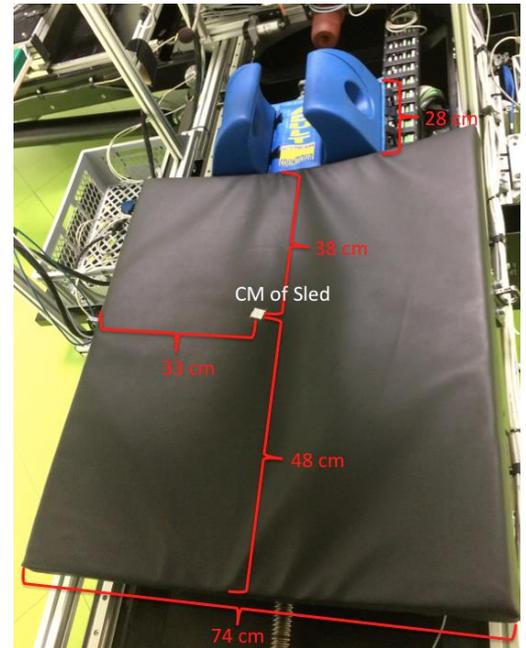


Figure 12. Sled Dimension

- Additional Equipment on Test Subject** includes a safety harness, three accelerometers on left and right shins and on waist as a belt, and an Actibelt with a marker on waist (as shown on figure 14). Furthermore, during centrifugation, Finapress is used for medical (blood pressure) monitoring.



Figure 13. Extra Pillow



Figure 14. Equipment on Test Subject

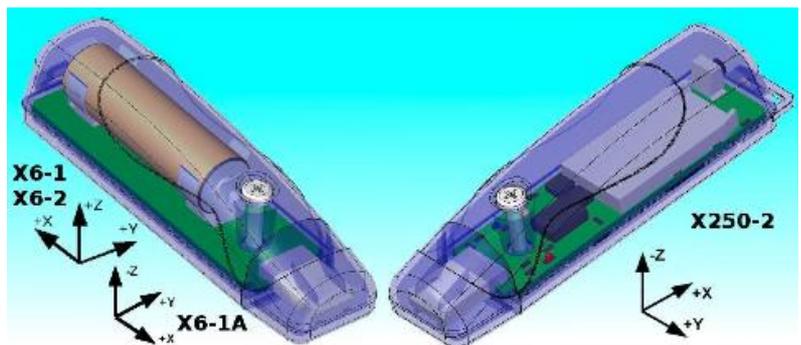


Figure 15. Accelerometers

## Control Station

The upright squatting on ground experiment is also conducted as the control experiment in order to compare the body movements, forces, and torques. As shown on figure 16, the equipment at the control station includes the vertical sled on the metal structure, two force plates, motivation tool, and six motion capturing cameras with the Vicon Nexus software as same as on the centrifuge. The sled on the control station gives no additional weight to the test subject because it was designed to have the same weight hanging on the backside to balance the sled.



Figure 16. Control Station

## Chapter 9. Methodology

1. **Gather information and develop a biomechanical model** for AG (supine) squat exercise by obtaining joint orientations, displacements, velocities and accelerations from the Inverse Kinematics method given body part's positions as the inputs. Then, use the data of the joint orientations, displacements, velocities, accelerations, and external forces and torques to calculate the joint torques and forces and show the results. This is called "Inverse Dynamics" method as shown in figure 17.

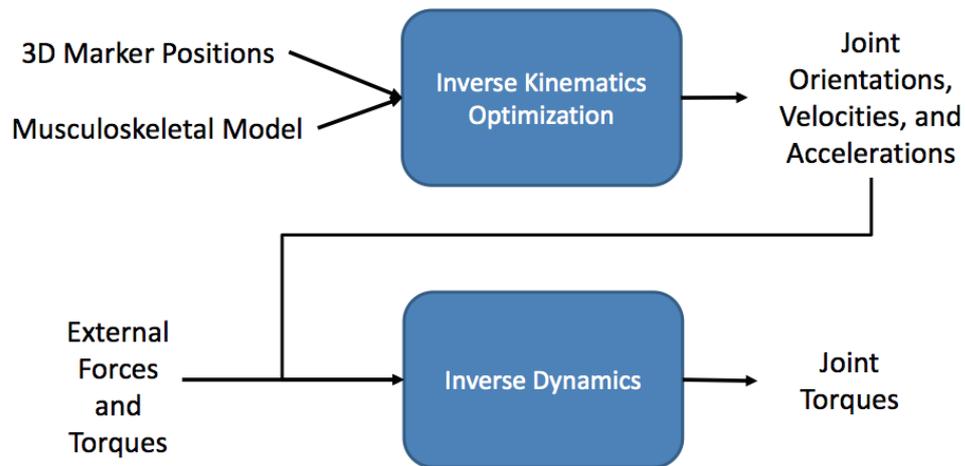


Figure 17. Inverse Dynamics method

[Lecture of MIT Human System Engineering course by Prof. Stirling, 2015]

2. **Simulate the biomechanical model** for AG squat exercise using MATLAB. The input parameters such as radius of the centrifuge, rotation rate, rotation direction (clockwise vs. counterclockwise), and the test subject's height, weight, and lengths of body parts need to be adjustable. The simulation needs to demonstrate foot reaction forces, torques, and body movements due to the Coriolis effect and g-gradient.
3. **Validate the biomechanical model by human experiments.** Experimental design and exercise protocol need to be developed. Then, test subjects will be recruited to do the experiments on the next generation DLR Short-Arm Human Centrifuge (envifuge) under the control and supervision by physicians for safety purpose. The data will be collected by using the Motion Capturing System on the centrifuge.
4. **Analyze data and conclude. Then, write a report.**

**Table 4. Schedule**

<b>No.</b>	<b>Activity</b>	<b>Timeline</b>
1	Gather information (literature review)	January, 2016
2	Define clear scopes	February, 2016
3	Develop squat exercise protocol and experiment protocol	February, 2016
4	Recruit test subjects and prepare documents	February - March, 2016
5	Develop draft model and simulation of squat on the centrifuge	February - March, 2016
6	Check and prepare equipment	February - March, 2016
7	Check timetables and schedule for test and experiment runs	March, 2016
8	Dry runs (run through the experiment protocol)	March, 2016
9	Test runs	March, 2016
10	Measure body parts of the subjects	April 7 – 29, 2016
11	Experiment runs (collect data on centrifuge and control station)	April 7 – 29, 2016
12	Check, process and analyze data	April 14 – 30, 2016
13	Submit thesis abstract	April 29, 2016
14	Validate the model and simulation of squat on the centrifuge	May 1 – 5, 2016
15	Start writing the thesis report and making a presentation	May 6, 2016
16	Submit final thesis draft report	May 11, 2016
17	Submit final thesis report	May 30, 2016
18	Prepare for thesis defense	June 1 – 10, 2016

## 9.1 Biomechanical Models, Kinematics Analysis and Torque Calculations

The 2D body diagrams for supine squats on centrifuge as shown on figure 18 were developed based on Duda's two-dimensional squat biomechanics diagram [2] shown on figure 3. However, these new developed diagrams take the length between the ankle and the heel into account and, for calculations, the leg was segmented into 5 sub-segments including upper thigh, mid-thigh, lower thigh, upper shin and lower shin. Also the equations of the velocities and accelerations of the body segments were developed by taking the first and the second derivatives of the positions, where x axis is along the radius of the centrifuge, y axis is along the vertical direction from the base of the centrifuge upward and the origin coordinate is at the bottom part of the force plate as shown on figure 18.

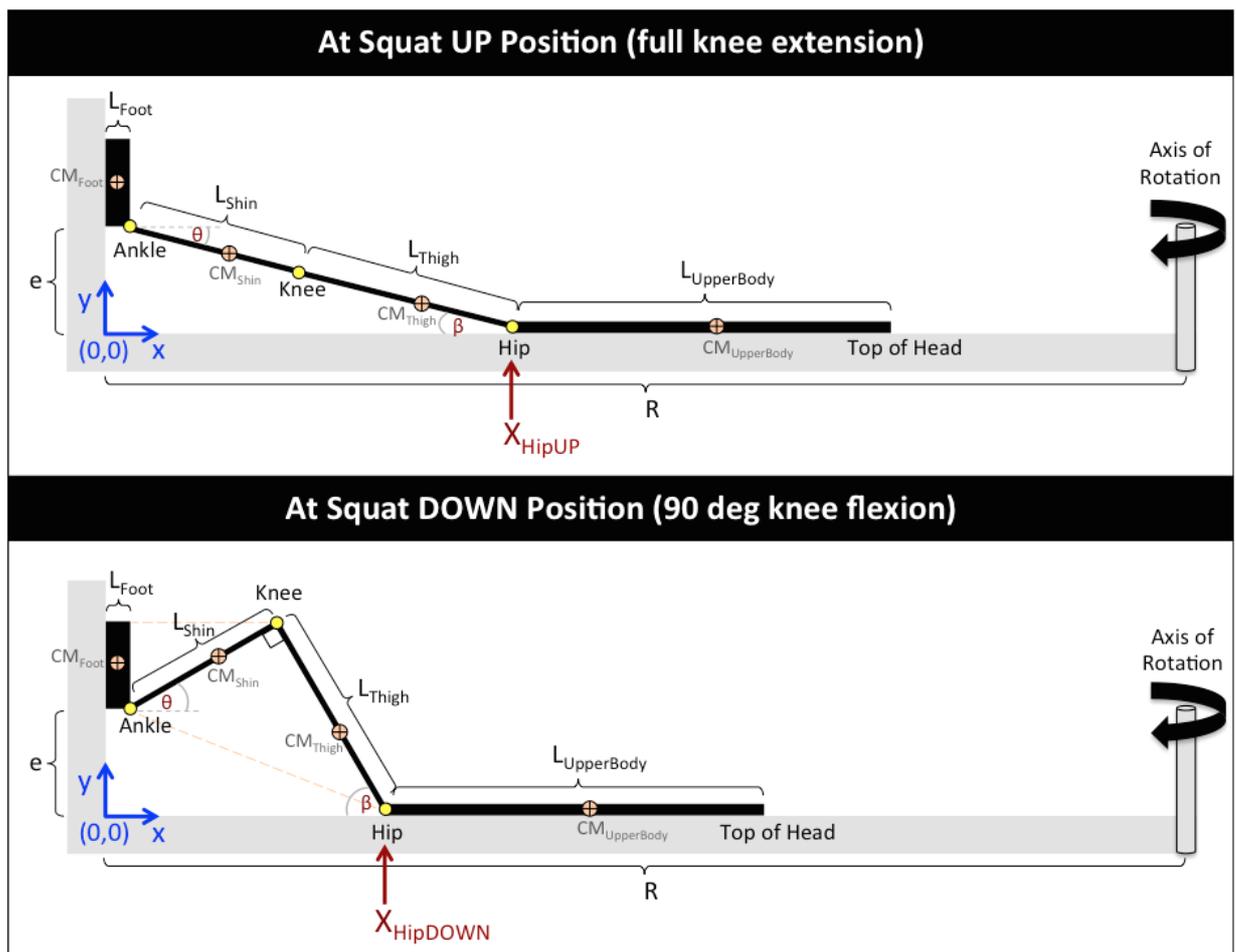


Figure 18. 2D body diagrams for supine squats on centrifuge

Positions of the hip joint ( $X_{Hip}$ ) from the force plate (the origin coordinate) can be defined as:  
At knee extension (squat up) position,

$$X_{HipUP} = \sqrt{(L_{Thigh} + L_{Shin})^2 - e^2} + L_{Foot} \quad (\text{Eqn.1})$$

At 90-degree knee flexion (squat down) position,

$$X_{HipDOWN} = \sqrt{(L_{Thigh})^2 + (L_{Shin})^2 - e^2} + L_{Foot} \quad (\text{Eqn.2})$$

where

$L_{Thigh}$  : Length of Thigh (from hip to knee)

$L_{Shin}$  : Length of Shin (from knee to ankle)

$L_{Foot}$  : Length of Foot (from ankle to heel)

$L_{UpperBody}$  : Length of Upper Body (from top of head to hip)

$e$  : Foot Elevation

$R$  : Radius of rotation (from the axis of rotation of the centrifuge to force plate position)

According to the 2D body diagrams of the kinematic system on figure 18, by restricting to this two-dimensional approach, there is only one degree of freedom remaining due to the kinematic constraints. This means when one joint is blocked, the entire motion is blocked. This one degree of freedom is also the reason why by a given hip position all the other parameters are defined.

### Six equations derived from the 2D body diagrams

#### On x-axis

Start from the position of the hip joint on x-axis.

$$X_{Hip} = L_{Thigh} \cos(\beta) + L_{Shin} \cos(\theta) + L_{Foot} \quad (\text{Eqn. 3})$$

Take the first derivative of Eqn. 3, we get the velocity of the hip:  $\frac{dX_{Hip}}{dt} = V_{Hip}$

$$V_{Hip} = -\omega_{Thigh} L_{Thigh} \sin(\beta) - \omega_{Shin} L_{Shin} \sin(\theta) \quad (\text{Eqn. 4})$$

Take the second derivative of Eqn. 3, we get the acceleration of the hip:  $\frac{dV_{Hip}}{dt} = A_{Hip}$

$$A_{Hip} = -L_{Thigh} [(\omega_{Thigh})^2 \cos(\beta) + \alpha_{Thigh} \sin(\beta)] - L_{Shin} [(\omega_{Shin})^2 \cos(\theta) + \alpha_{Shin} \sin(\theta)] \quad (\text{Eqn. 5})$$

#### On y-axis

$$e = L_{Thigh} \sin(\beta) - L_{Shin} \sin(\theta) \quad (\text{Eqn. 6})$$

Take the first derivative of Eqn. 6, we get:

$$0 = \omega_{Thigh} L_{Thigh} \cos(\beta) - \omega_{Shin} L_{Shin} \cos(\theta) \quad (\text{Eqn. 7})$$

Take the second derivative of Eqn. 6, we get:

$$0 = L_{Thigh} [-(\omega_{Thigh})^2 \sin(\beta) + \alpha_{Thigh} \cos(\beta)] - L_{Shin} [-(\omega_{Shin})^2 \sin(\theta) + \alpha_{Shin} \cos(\theta)] \quad (\text{Eqn. 8})$$

where there are six unknown (angular) parameters:

$\beta =$ Thigh elevation angle	$\theta =$ Shin elevation angle
$\omega_{Thigh} = \frac{d\beta}{dt} =$ Angular velocity of thigh	$\omega_{Shin} = \frac{d\theta}{dt} =$ Angular velocity of shin
$\alpha_{Thigh} = \frac{d\omega_{Thigh}}{dt} =$ Angular acceleration of thigh	$\alpha_{Shin} = \frac{d\omega_{Shin}}{dt} =$ Angular acceleration of shin

These parameters are solved using the non-linear equations solver method named fsolve on MATLAB. From the hip positions, we can derive the equations for positions of knee ( $X_{Knee}$ ), center of mass of Thigh ( $X_{cmThigh}$ ) and center of mass of Shin ( $X_{cmShin}$ ):

$$X_{Knee} = X_{Hip} - L_{Thigh} \cos(\beta) \quad (\text{Eqn. 9})$$

$$\frac{dX_{Knee}}{dt} = V_{Knee} = V_{Hip} + \omega_{Thigh} L_{Thigh} \sin(\beta) \quad (\text{Eqn. 10})$$

$$\frac{dV_{Knee}}{dt} = A_{Knee} = A_{Hip} + L_{Thigh} [(\omega_{Thigh})^2 \cos(\beta) + \alpha_{Thigh} \sin(\beta)] \quad (\text{Eqn. 11})$$

$$X_{cmThigh} = X_{Hip} - R_{cmThigh} \cos(\beta) \quad (\text{Eqn. 12})$$

$$\frac{dX_{cmThigh}}{dt} = V_{cmThigh} = V_{Hip} + \omega_{Thigh} R_{cmThigh} \sin(\beta) \quad (\text{Eqn. 13})$$

$$\frac{dV_{cmThigh}}{dt} = A_{cmThigh} = A_{Hip} + R_{cmThigh} [(\omega_{Thigh})^2 \cos(\beta) + \alpha_{Thigh} \sin(\beta)] \quad (\text{Eqn. 14})$$

$$X_{cmShin} = X_{Knee} - R_{cmShin} \cos(\theta) \quad (\text{Eqn. 15})$$

$$\frac{dX_{cmShin}}{dt} = V_{cmShin} = V_{Knee} + \omega_{Shin} R_{cmShin} \sin(\theta) \quad (\text{Eqn. 16})$$

$$\frac{dV_{cmShin}}{dt} = A_{cmShin} = A_{Knee} + R_{cmShin} [(\omega_{Shin})^2 \cos(\theta) + \alpha_{Shin} \sin(\theta)] \quad (\text{Eqn. 17})$$

The center of mass of upper body ( $X_{cmUpperBody}$ ) moves as the same rate as the hip:

$$X_{cmUpperBody} = X_{Hip} + (L_{UpperBody} - R_{cmUpperBody}) \quad (\text{Eqn. 18})$$

$$V_{cmUpperBody} = V_{Hip} \quad (\text{Eqn. 19})$$

$$A_{cmUpperBody} = A_{Hip} \quad (\text{Eqn. 20})$$

The center of mass of foot ( $X_{cmFoot}$ ) is fixed on the force plate:

$$X_{cmFoot} = \frac{1}{2} L_{Foot} \quad (\text{Eqn. 21})$$

$$V_{cmFoot} = 0 \quad (\text{Eqn. 22})$$

$$A_{cmFoot} = 0 \quad (\text{Eqn. 23})$$

where

$M_{UpperBody}$  : mass of upper body (including head, torso, 2 arms, and equipment)

$M_{Thigh}$  : mass of 1 thigh (with equipment)

$M_{Shin}$  : mass of 1 shin (with equipment)

$M_{Foot}$  : mass of 1 foot (with equipment)

$R_{cmUpperBody}$  : length between the center of mass of upper body ( $CM_{UpperBody}$ ) and the top of head

$R_{cmThigh}$  : length between the center of mass of thigh ( $CM_{Thigh}$ ) and the hip

$R_{cmShin}$  : length between the center of mass of shin ( $CM_{Shin}$ ) and the knee

$R_{cmFoot}$  : length between the center of mass of foot ( $CM_{Foot}$ ) and the ankle

$X_{cm_i}$  : position on x-axis of the center of mass of body part i from the force plate (the origin coordinate)

$V_{cm_i}$  : velocity on x-axis of the center of mass of body part i

$A_{cm_i}$  : acceleration on x-axis of the center of mass of body part i

## Calculation of Foot Reaction Forces (on the centrifuge)

The foot reaction forces during squatting on the centrifuge are the combination of centrifugal forces from inertial body ( $m_i\omega^2R_i$ ) and the additional forces due to dynamic squat accelerations ( $m_i a_i$ ).

$$\begin{aligned} \text{FootForce\_squat\_centrifuge}(t) = & M_{\text{UpperBody}} [(\omega_{\text{Centrifuge}})^2 (R - X_{\text{cmUpperBody}}(t)) + A_{\text{Hip}}(t)] \\ & + 2 M_{\text{Thigh}} [(\omega_{\text{Centrifuge}})^2 (R - X_{\text{cmThigh}}(t)) + A_{\text{cmThigh}}(t)] \\ & + 2 M_{\text{Shin}} [(\omega_{\text{Centrifuge}})^2 (R - X_{\text{cmShin}}(t)) + A_{\text{cmShin}}(t)] \\ & + 2 M_{\text{Foot}} [(\omega_{\text{Centrifuge}})^2 (R - X_{\text{cmFoot}}(t))] \end{aligned} \quad (\text{Eqn. 24})$$

## Analysis on effects of body segmentation in centrifugation environment

On the centrifuge, the gravity level (g-level) varies along the radius. This may cause different magnitudes of forces and torques on each body parts. In this study, the body was segmented by using the Yeadon's model [13] as shown on figure 19. The upper body includes head, torso, and two arms. One thigh has three segments: upper thigh, mid-thigh and lower thigh. One shin has two segments: upper shin and lower shin. The parts lower than ankle joint level are considered as one foot.

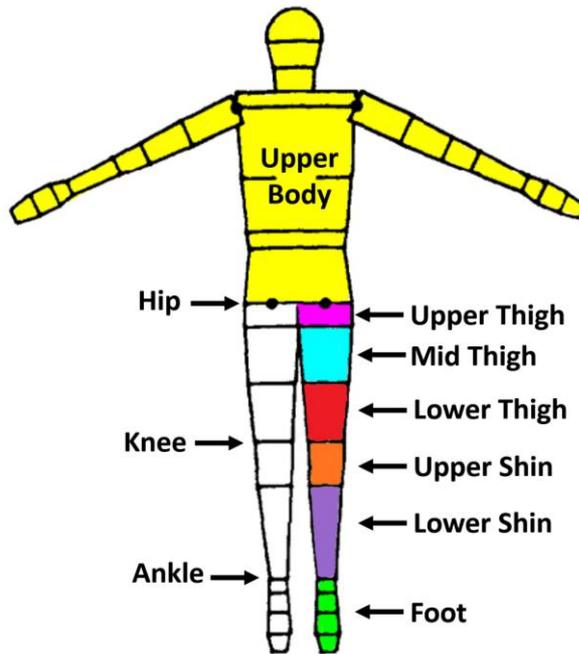


Figure 19. Body segmentation edited from Yeadon's model [13]

$R_{\text{cmUpperThigh}}$  : length between the center of mass of upper thigh ( $CM_{\text{UpperThigh}}$ ) and the hip

$R_{\text{cmMidThigh}}$  : length between the center of mass of mid-thigh ( $CM_{\text{MidThigh}}$ ) and the hip

$R_{\text{cmLowerThigh}}$  : length between the center of mass of lower thigh ( $CM_{\text{LowerThigh}}$ ) and the hip

$R_{\text{cmUpperShin}}$  : length between the center of mass of upper shin ( $CM_{\text{UpperShin}}$ ) and the knee

$R_{\text{cmLowerShin}}$  : length between the center of mass of lower shin ( $CM_{\text{LowerShin}}$ ) and the knee

## Calculation of Coriolis Forces

In order to compare the effects of the Coriolis forces on leg segments, the Coriolis forces acting on the center of mass of thigh ( $\text{CoriolisForce}_{\text{Thigh}}$ ) were calculated in comparison with the summation of the Coriolis forces acting on the center of mass of upper thigh, mid-thigh and lower thigh ( $\text{CoriolisForce}_{\text{UpperThigh}} + \text{CoriolisForce}_{\text{MidThigh}} + \text{CoriolisForce}_{\text{LowerThigh}}$ ).

At time  $t$ ,

$$\text{CoriolisForce}_{\text{Thigh}}(t) = 2 M_{\text{Thigh}} \cdot \omega_{\text{Centrifuge}} \cdot V_{\text{cmThigh}}(t) \quad (\text{Eqn. 25})$$

$$\text{CoriolisForce}_{\text{UpperThigh}}(t) = 2 M_{\text{UpperThigh}} \cdot \omega_{\text{Centrifuge}} \cdot V_{\text{cmUpperThigh}}(t) \quad (\text{Eqn. 26})$$

$$\text{CoriolisForce}_{\text{MidThigh}}(t) = 2 M_{\text{MidThigh}} \cdot \omega_{\text{Centrifuge}} \cdot V_{\text{cmMidThigh}}(t) \quad (\text{Eqn. 27})$$

$$\text{CoriolisForce}_{\text{LowerThigh}}(t) = 2 M_{\text{LowerThigh}} \cdot \omega_{\text{Centrifuge}} \cdot V_{\text{cmLowerThigh}}(t) \quad (\text{Eqn. 28})$$

Similarly, the Coriolis forces acting on the center of mass of shin ( $\text{CoriolisForce}_{\text{Shin}}$ ) were calculated in comparison with the summation of the Coriolis forces acting on the center of mass of upper shin and lower shin ( $\text{CoriolisForce}_{\text{UpperShin}} + \text{CoriolisForce}_{\text{LowerShin}}$ ).

At time  $t$ ,

$$\text{CoriolisForce}_{\text{Shin}}(t) = 2 M_{\text{Shin}} \cdot \omega_{\text{Centrifuge}} \cdot V_{\text{cmShin}}(t) \quad (\text{Eqn. 29})$$

$$\text{CoriolisForce}_{\text{UpperShin}}(t) = 2 M_{\text{UpperShin}} \cdot \omega_{\text{Centrifuge}} \cdot V_{\text{cmUpperShin}}(t) \quad (\text{Eqn. 30})$$

$$\text{CoriolisForce}_{\text{LowerShin}}(t) = 2 M_{\text{LowerShin}} \cdot \omega_{\text{Centrifuge}} \cdot V_{\text{cmLowerShin}}(t) \quad (\text{Eqn. 31})$$

## Calculation of torques on joints during squatting on the centrifuge

On the centrifuge, there are forces acting on three-dimensional axes, which cause torques on knee joints, ankle joints and hip joints. In this calculation, we considered only torques on one knee joint and on one ankle joint caused by the forces on x axis, and torques on one knee joint, on one ankle joint and on one hip joint caused by the forces on z axis.

The magnitude of torque ( $\tau$ ) depends on three quantities: the force applied ( $F$ ), the length of the lever arm connecting the axis to the point of force application ( $r$ ), and the angle between the force vector and the lever arm ( $\phi$ ), which can be written as:  $\tau = |r| |F| \sin(\phi)$

According to figure 18, the knee joint can move freely with no restriction, unlike the ankle joint that is fixed on the force plate and the hip joint that is located on the sled, which can move only along the x axis. Thus, on the knee joint, two lever arms (thigh and shin) were taken into account, which the forces from the mass of the upper body were considered as applying at the end of the thigh (hip joint) position. On an ankle joint, only one lever arm (shin) was taken into account; hence, the forces from the masses of the upper body and the thigh were considered as applying at the end of the shin (knee joint) position. On a hip joint, only one lever arm (thigh) was taken into account; thus, the forces from the mass of the shin were considered as applying at the end of the thigh (knee joint) position. Moreover, the forces from the mass of the upper body was divided by 2, assuming that the forces were distributed to the two legs equally. Also, the upper body was supported by the sled underneath, which means the Coriolis force and the force from the weight of the upper body could be ignored.

Furthermore, the torques acting on the center of mass of thigh were calculated in comparison with the summation of the torques acting on the center of mass of upper thigh, mid-thigh and lower thigh. Similarly, the torques acting on the center of mass of shin were calculated in comparison with the summation of the torques acting on the center of mass of upper shin and lower shin.

### Torques on X-axis

On x-axis, there are two types of forces acting on each body part including the centrifugal forces ( $m_i \omega^2 R_i$ ) and the forces from dynamic squat accelerations ( $m_i a_i$ ). Since the ankle joint is fixed, the forces acting on the shin could not cause a torque on the knee joint. Thus, in this case, only the forces acting on the upper body and on the thigh could cause torques on the knee joint. However, the forces acting on the upper body, on the thigh, and on the shin could cause torques on the ankle joint.

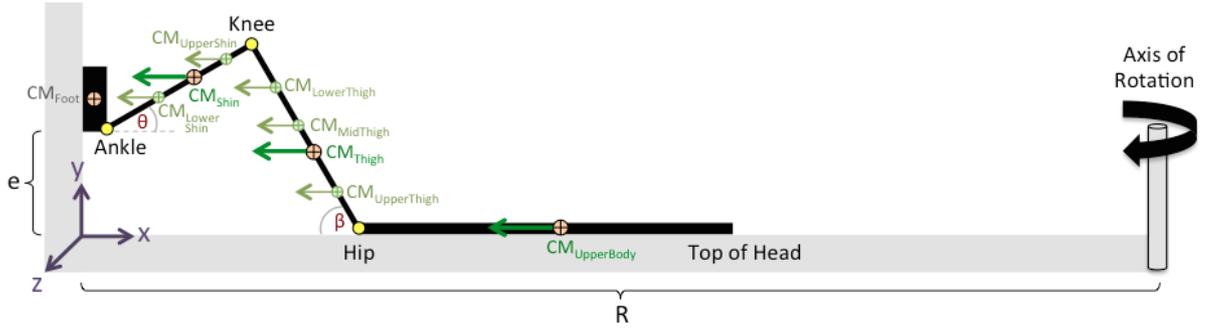


Figure 20. Body diagram of forces on x-axis on the centrifuge for torques calculation

### Torques on X-axis due to centrifugal forces ( $m_i \omega^2 R_i$ )

At a knee joint,

$$\tau_{x1\_Knee\_UpperBody} = \frac{1}{2} M_{UpperBody} (\omega_{Centrifuge})^2 (R - X_{cmUpperBody}) (L_{Thigh}) \sin(\beta) \quad (\text{Eqn. 32})$$

$$\tau_{x1\_Knee\_Thigh} = M_{Thigh} (\omega_{Centrifuge})^2 (R - X_{cmThigh}) (L_{Thigh} - R_{cmThigh}) \sin(\beta) \quad (\text{Eqn. 33})$$

$$\tau_{x1\_Knee\_UpperThigh} = M_{UpperThigh} (\omega_{Centrifuge})^2 (R - X_{cmUpperThigh}) (L_{Thigh} - R_{cmUpperThigh}) \sin(\beta) \quad (\text{Eqn. 34})$$

$$\tau_{x1\_Knee\_MidThigh} = M_{MidThigh} (\omega_{Centrifuge})^2 (R - X_{cmMidThigh}) (L_{Thigh} - R_{cmMidThigh}) \sin(\beta) \quad (\text{Eqn. 35})$$

$$\tau_{x1\_Knee\_LowerThigh} = M_{LowerThigh} (\omega_{Centrifuge})^2 (R - X_{cmLowerThigh}) (L_{Thigh} - R_{cmLowerThigh}) \sin(\beta) \quad (\text{Eqn. 36})$$

At an ankle joint,

$$\tau_{x1\_Ankle\_UpperBody} = \frac{1}{2} M_{UpperBody} (\omega_{Centrifuge})^2 (R - X_{cmUpperBody}) (L_{Shin}) \sin(\theta) \quad (\text{Eqn. 37})$$

$$\tau_{x1\_Ankle\_Thigh} = M_{Thigh} (\omega_{Centrifuge})^2 (R - X_{cmThigh}) (L_{Shin}) \sin(\theta) \quad (\text{Eqn. 38})$$

$$\tau_{x1\_Ankle\_Shin} = M_{Shin} (\omega_{Centrifuge})^2 (R - X_{cmShin}) (L_{shin} - R_{cmShin}) \sin(\theta) \quad (\text{Eqn. 39})$$

$$\tau_{x1\_Ankle\_UpperShin} = M_{UpperShin} (\omega_{Centrifuge})^2 (R - X_{cmUpperShin}) (L_{shin} - R_{cmUpperShin}) \sin(\theta) \quad (\text{Eqn. 40})$$

$$\tau_{x1\_Ankle\_LowerShin} = M_{LowerShin} (\omega_{Centrifuge})^2 (R - X_{cmLowerShin}) (L_{shin} - R_{cmLowerShin}) \sin(\theta) \quad (\text{Eqn. 41})$$

### Torques on X-axis due to forces from dynamic squat accelerations ( $m_i a_i$ )

At a knee joint,

$$\tau_{x2\_Knee\_UpperBody} = \frac{1}{2} M_{UpperBody} a_{UpperBody} (L_{Thigh}) \sin(\beta) \quad (\text{Eqn. 42})$$

$$\tau_{x2\_Knee\_Thigh} = M_{thigh} a_{Thigh} (L_{Thigh} - R_{cmThigh}) \sin(\beta) \quad (\text{Eqn. 43})$$

$$\tau_{x2\_Knee\_UpperThigh} = M_{UpperThigh} a_{UpperThigh} (L_{Thigh} - R_{cmUpperThigh}) \sin(\beta) \quad (\text{Eqn. 44})$$

$$\tau_{x2\_Knee\_MidThigh} = M_{MidThigh} a_{MidThigh} (L_{Thigh} - R_{cmMidThigh}) \sin(\beta) \quad (\text{Eqn. 45})$$

$$\tau_{x2\_Knee\_LowerThigh} = M_{LowerThigh} a_{LowerThigh} (L_{Thigh} - R_{cmLowerThigh}) \sin(\beta) \quad (\text{Eqn. 46})$$

At an ankle joint,

$$\tau_{x2\_Ankle\_UpperBody} = \frac{1}{2} M_{UpperBody} a_{UpperBody} (L_{Shin}) \sin(\theta) \quad (\text{Eqn. 47})$$

$$\tau_{x2\_Ankle\_Thigh} = M_{Thigh} a_{Thigh} (L_{Shin}) \sin(\theta) \quad (\text{Eqn. 48})$$

$$\tau_{x2\_Ankle\_Shin} = M_{Shin} a_{Shin} (L_{shin} - R_{cmShin}) \sin(\theta) \quad (\text{Eqn. 49})$$

$$\tau_{x2\_Ankle\_UpperShin} = M_{UpperShin} a_{UpperShin} (L_{shin} - R_{cmUpperShin}) \sin(\theta) \quad (\text{Eqn. 50})$$

$$\tau_{x2\_Ankle\_LowerShin} = M_{LowerShin} a_{LowerShin} (L_{shin} - R_{cmLowerShin}) \sin(\theta) \quad (\text{Eqn. 51})$$

### Torques on Z-axis due to Coriolis forces ( $2 m_i \omega v_i$ )

There is one type of forces acting on z-axis: Coriolis Force ( $2 m_i \omega v_i$ ) acting on the thigh and the shin. As seen on figure 21, since the ankle joint is fixed and the hip joint can move only along the x-axis, but the knee joint can move freely. Thus, there is no torque on the knee joint, but there are equal torques happened at the ankle joint and the hip joint at the same time. The torques can be calculated by adding a line of lever arm between the hip joint and the ankle joint as shown on figure 21. The angle ( $\delta$ ) between the line of the lever arm and the x-axis can be calculated from:

$$\tan(\delta) = \frac{e}{X_{Hip} - L_{Foot}} \longrightarrow \delta = \arctan\left(\frac{e}{X_{Hip} - L_{Foot}}\right)$$

The angle ( $\epsilon$ ) between the line of the lever arm and the thigh can be calculated from:  $\epsilon = \beta - \delta$

The angle ( $\gamma$ ) between the line of the lever arm and the shin can be calculated from:  $\gamma = \theta + \delta$

where  $\beta$  is the thigh elevation angle and  $\theta$  is the shin elevation angle

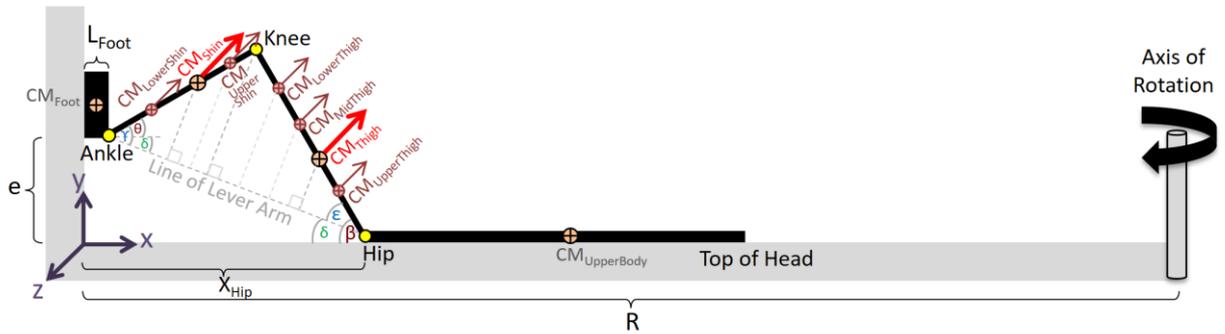


Figure 21. Body diagram of forces on z-axis on the centrifuge for torques calculation

The equal torques are happened at an ankle joint and a hip joint at the same time:

$$\tau_{z\_Thigh} = 2 M_{Thigh} \omega_{Centrifuge} V_{cmThigh} (R_{cmThigh}) \sin(\epsilon) \quad (\text{Eqn. 52})$$

$$\tau_{z\_UpeerThigh} = 2 M_{UpperThigh} \omega_{Centrifuge} V_{cmUpperhigh} (R_{cmUpperThigh}) \sin(\epsilon) \quad (\text{Eqn. 53})$$

$$\tau_{z\_MidThigh} = 2 M_{MidThigh} \omega_{Centrifuge} V_{cmMidThigh} (R_{cmMidThigh}) \sin(\epsilon) \quad (\text{Eqn. 54})$$

$$\tau_{z\_LowerThigh} = 2 M_{LowerThigh} \omega_{Centrifuge} V_{cmLowerThigh} (R_{cmLowerThigh}) \sin(\epsilon) \quad (\text{Eqn. 55})$$

$$\tau_{z\_Shin} = 2 M_{Shin} \omega_{Centrifuge} V_{cmShin} (L_{Shin} - R_{cmShin}) \sin(\gamma) \quad (\text{Eqn. 56})$$

$$\tau_{z\_UpperShin} = 2 M_{UpperShin} \omega_{Centrifuge} V_{cmUpperShin} (L_{Shin} - R_{cmUpperShin}) \sin(\gamma) \quad (\text{Eqn. 57})$$

$$\tau_{z\_LowerShin} = 2 M_{Shin} \omega_{Centrifuge} V_{cmLowerShin} (L_{Shin} - R_{cmLowerShin}) \sin(\gamma) \quad (\text{Eqn. 58})$$

### Torques on Y-axis due to weights ( $m_i g$ )

There is one type of forces acting on y-axis: weight ( $m_i g$ ) of the thigh and the shin. The forces from the weights of the foot and the upper body were neglected because the feet were supported by the foot holders and the upper body was supported by the sled. However, the torque from weight of thigh and the torque from weight of shin are in the opposite directions because both of the torques extend the knee angles. This is very tricky for the calculations and will be analyzed in the future study.

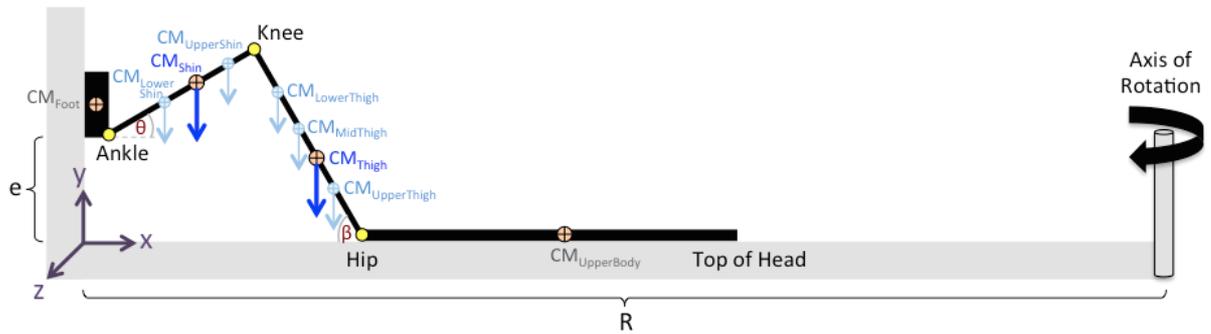


Figure 22. Body diagram of forces on y-axis on the centrifuge for torques calculation

## Calculation of torques on joints during squatting on the control station

On the control station, there are only two types of forces on the vertical axis that cause the joint torques: weight ( $m_i g$ ), which  $g = 9.81 \text{ m/s}^2$ , and forces from dynamic squat accelerations ( $m_i a_i$ ). In addition, the mass of the upper body was divided by 2, assuming that the forces were distributed to the two legs equally.

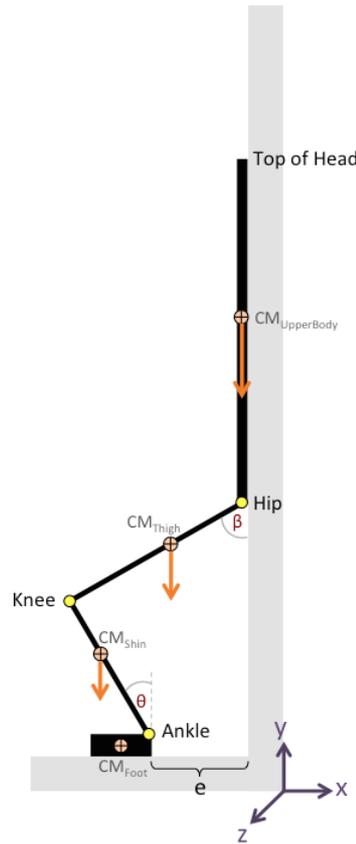


Figure 23. Body diagram of forces on y-axis on the control station for torques calculation

### Torques due to weights ( $m_i g$ )

At a knee joint,

$$\tau_{\text{Control\_Knee\_UpperBody}} = \frac{1}{2} M_{\text{UpperBody}} g (L_{\text{Thigh}}) \sin(\beta) \quad (\text{Eqn. 59})$$

$$\tau_{\text{Control\_Knee\_Thigh}} = M_{\text{Thigh}} g (L_{\text{Thigh}} - R_{\text{cmThigh}}) \sin(\beta) \quad (\text{Eqn. 60})$$

$$\tau_{\text{Control\_Knee\_Shin}} = M_{\text{Shin}} g (R_{\text{cmShin}}) \sin(\theta) \quad (\text{Eqn. 61})$$

At an ankle joint,

$$\tau_{\text{Control\_Ankle\_UpperBody}} = \frac{1}{2} M_{\text{UpperBody}} g (L_{\text{Shin}}) \sin(\theta) \quad (\text{Eqn. 62})$$

$$\tau_{\text{Control\_Ankle\_Thigh}} = M_{\text{Thigh}} g (L_{\text{Shin}}) \sin(\theta) \quad (\text{Eqn. 63})$$

$$\tau_{\text{Control\_Ankle\_Shin}} = M_{\text{Shin}} g (L_{\text{Shin}} - R_{\text{cmShin}}) \sin(\theta) \quad (\text{Eqn. 64})$$

### Torques due to forces from dynamic squat accelerations ( $m_i a_i$ )

At a knee joint,

$$\tau_{\text{Control\_Knee\_UpperBody}} = \frac{1}{2} M_{\text{UpperBody}} a_{\text{UpperBody}} (L_{\text{Thigh}}) \sin(\beta) \quad (\text{Eqn. 65})$$

$$\tau_{\text{Control\_Knee\_Thigh}} = M_{\text{Thigh}} a_{\text{Thigh}} (L_{\text{Thigh}} - R_{\text{cmThigh}}) \sin(\beta) \quad (\text{Eqn. 66})$$

$$\tau_{\text{Control\_Knee\_Shin}} = M_{\text{Shin}} a_{\text{Shin}} (R_{\text{cmShin}}) \sin(\theta) \quad (\text{Eqn. 67})$$

At an ankle joint,

$$\tau_{\text{Control\_Ankle\_UpperBody}} = \frac{1}{2} M_{\text{UpperBody}} a_{\text{UpperBody}} (L_{\text{Shin}}) \sin(\theta) \quad (\text{Eqn. 68})$$

$$\tau_{\text{Control\_Ankle\_Thigh}} = M_{\text{Thigh}} a_{\text{Thigh}} (L_{\text{Shin}}) \sin(\theta) \quad (\text{Eqn. 69})$$

$$\tau_{\text{Control\_Ankle\_Shin}} = M_{\text{Shin}} a_{\text{Shin}} (L_{\text{Shin}} - R_{\text{cmShin}}) \sin(\theta) \quad (\text{Eqn. 70})$$

### Calculation of Mechanical Work

The mechanical work ( $W$ ) was calculated by the integration (in time domain) of summation of the product of the magnitude of forces ( $F$ ) acting in the direction of squat motion and the velocities ( $v$ ) of body segments, which can be written as:

$$W = \int F dS = \int F \cdot v dt$$

The body segments include upper body, two thighs, two shins and two feet. The unit of work is Newton-meter ( $N \cdot m$ ) or joules ( $kg \cdot m^2/s^2$ ). We can convert the work to the unit of calories by using  $1 \text{ joule} = 0.239005736 \text{ calories}$ .

On the centrifuge, the forces acting in the direction of squat motion are centrifugal forces ( $m_i \omega^2 R_i$ ) and forces from dynamic squat accelerations ( $m_i a_i$ ). Thus, at time  $t$ , the summation of the product of the magnitude of forces and the velocities ( $v$ ) of body segments is:

$$\begin{aligned} F \cdot V(t) = & M_{\text{UpperBody}} [(\omega_{\text{Centrifuge}})^2 (R - X_{\text{cmUpperBody}}(t)) + A_{\text{UpperBody}}(t)] \cdot V_{\text{UpperBody}}(t) \\ & + 2 M_{\text{Thigh}} [(\omega_{\text{Centrifuge}})^2 (R - X_{\text{cmThigh}}(t)) + A_{\text{cmThigh}}(t)] \cdot V_{\text{cmThigh}}(t) \\ & + 2 M_{\text{Shin}} [(\omega_{\text{Centrifuge}})^2 (R - X_{\text{cmShin}}(t)) + A_{\text{cmShin}}(t)] \cdot V_{\text{cmShin}}(t) \\ & + 2 M_{\text{Foot}} [(\omega_{\text{Centrifuge}})^2 (R - X_{\text{cmFoot}}(t)) + A_{\text{cmFoot}}(t)] \cdot V_{\text{cmFoot}}(t), \end{aligned} \quad (\text{Eqn. 71})$$

On the centrifuge, the forces acting in the direction of squat motion are weights ( $m_i g$ ) and forces from dynamic squat accelerations ( $m_i a_i$ ). Thus, at time  $t$ , the summation of the product of the magnitude of forces and the velocities ( $v$ ) of body segments is:

$$\begin{aligned} F \cdot V(t) = & M_{\text{UpperBody}} [g + A_{\text{UpperBody}}(t)] \cdot V_{\text{UpperBody}}(t) + 2 M_{\text{Thigh}} [g + A_{\text{cmThigh}}(t)] \cdot V_{\text{cmThigh}}(t) \\ & + 2 M_{\text{Shin}} [g + A_{\text{cmShin}}(t)] \cdot V_{\text{cmShin}}(t) + 2 M_{\text{Foot}} [g + A_{\text{cmFoot}}(t)] \cdot V_{\text{cmFoot}}(t), \end{aligned} \quad (\text{Eqn. 72})$$

For Eqn. 80 and Eqn. 81,  $A_{\text{cmFoot}}$  and  $V_{\text{cmFoot}}(t)$  are considered as zero.

Note that we used the absolute value of  $F \cdot V(t)$  for the integration.

## 9.2 Experiment Design

The experiment consists of three main sessions: 1) centrifuge at radius of 3.5 m, 2) centrifuge at radius of 3.5 m, and 3) control station. Each session has sub-sessions as shown on table 5.

**Table 5. The exercise protocol for motion capturing data of each test subject**

<b>Place and Condition</b>	<b>Body Motion</b>	<b>Position of Arms</b>	<b>Duration</b>	<b>File Name of Motion Capturing Data</b>
<b>Centrifuge at Radius of 3.5 m</b>	Static Postures at Up position	Arms Down	10 s	ERT_X_VIC_CL01
		Arms on Chest	10 s	
		Arms Up	10 s	
	Static Postures at Down position	Arms Down	10 s	ERT_X_VIC_CL01
	Arms on Chest	10 s		
	Arms Up	10 s		
<b>Centrifuge at Radius of 3.5 m</b>	1-min Squat with 2s pause <i>Profile Signal 1:</i> <i>Down – Up – Wait – Wait</i>	Arms Down	20 s	ERT_X_VIC_CL02
		Arms on Chest	20 s	
		Arms Up	20 s	
<b>Centrifuge at Radius of 3.5 m</b>	1-min Fast Squat (no pause) <i>Profile Signal 2:</i> <i>Down – Up – Down – Up</i>	Arms Down	20 s	ERT_X_VIC_CL03
		Arms on Chest	20 s	
		Arms Up	20 s	
<b>Centrifuge at Radius of 2.5 m</b>	Static Postures at Up position	Arms Down	10 s	ERT_X_VIC_CS01
		Arms on Chest	10 s	
		Arms Up	10 s	
	Static Postures at Down position	Arms Down	10 s	ERT_X_VIC_CS01
	Arms on Chest	10 s		
	Arms Up	10 s		
<b>Centrifuge at Radius of 2.5 m</b>	1-min Squat with 2s pause <i>Profile Signal 1:</i> <i>Down – Up – Wait – Wait</i>	Arms Down	20 s	ERT_X_VIC_CS02
		Arms on Chest	20 s	
		Arms Up	20 s	
<b>Centrifuge at Radius of 2.5 m</b>	1-min Fast Squat (no pause) <i>Profile Signal 2:</i> <i>Down – Up – Down – Up</i>	Arms Down	20 s	ERT_X_VIC_CS03
		Arms on Chest	20 s	
		Arms Up	20 s	
<b>Control Station</b>	1-min Squat with 2s pause <i>Profile Signal 1:</i> <i>Down – Up – Wait – Wait</i>	Arms Down	20 s	ERT_X_VIC_CO1
		Arms on Chest	20 s	
		Arms Up	20 s	
	1-min Fast Squat (no pause) <i>Profile Signal 2:</i> <i>Down – Up – Down – Up</i>	Arms Down	20 s	ERT_X_VIC_CO2
	Arms on Chest	20 s		
	Arms Up	20 s		

*X = Subject ID*

## Profile Signals

**Profile signal 1** is the 1-min squat with 2s pause. The rhythm is “Down – Up – Wait – Wait.” One repetition consists of 1 s downwards to a knee angle of 90°, 1 s upwards to start position, and wait at up position for 2 seconds. Thus, totally there are 15 repetitions; the first five repetitions with arms down, the second five repetitions with arms on chest, and the last five repetitions with arms up (shown on figure 24).

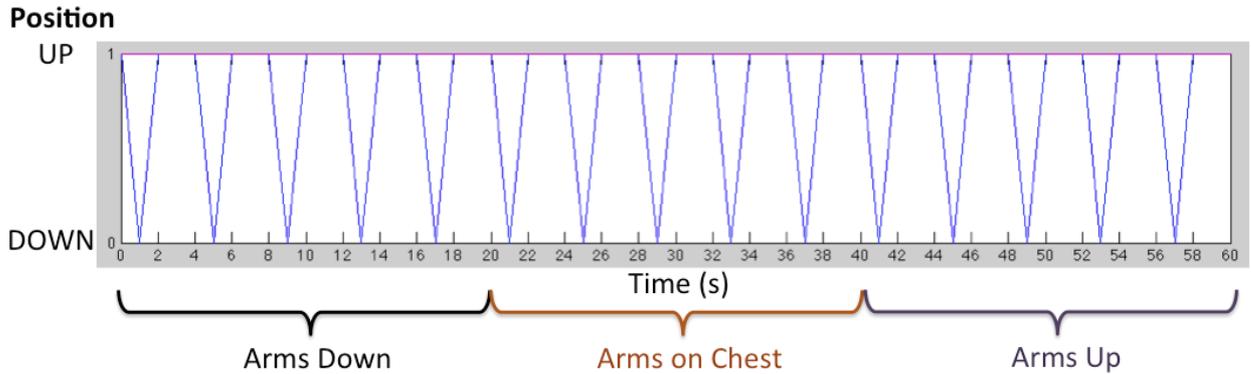


Figure 24. Profile Signal 1

**Profile signal 2** is the 1-min continuous squat with the rhythm “Down – Up – Down – Up.” One repetition consists of 1 s downwards to a knee angle of 90° and 1 s upwards to start position. Thus, totally there are 30 repetitions; the first ten repetitions with arms down, the second ten repetitions with arms on chest, and the last ten repetitions with arms up (shown on figure 25).

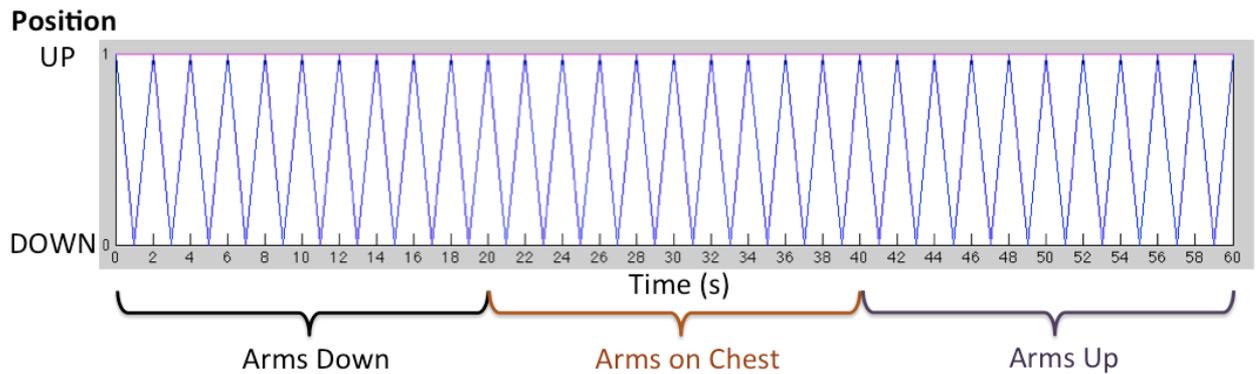
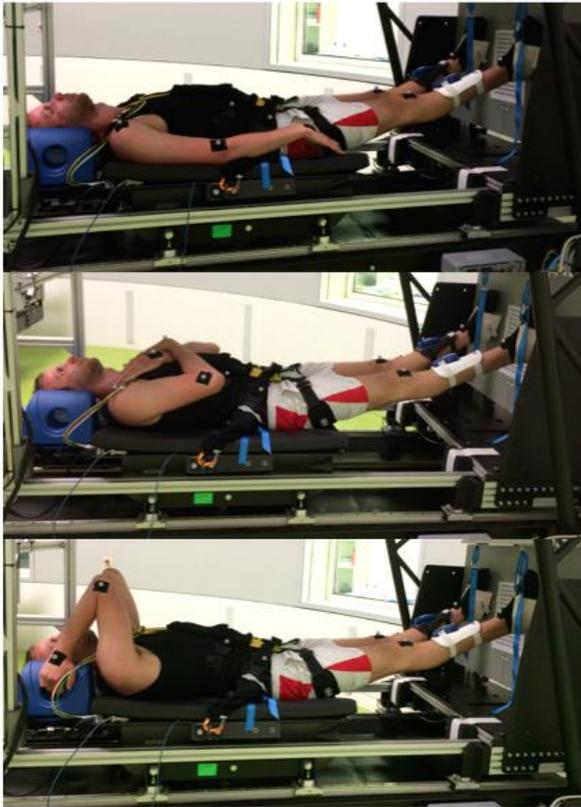


Figure 25. Profile Signal 2

## Positions of Arms

To test that mass distribution along the radius of the centrifuge influences the foot reaction forces resulted on the force plates due to gravity gradient, the subjects were told to perform the static postures and the dynamic squats with three different arm positions as shown on figure 26.



### Arms Down

Both arms are along the body downward to the feet.

### Arms on Chest

The center of mass of the two arms is assumed to be at the subject's nipple level.

### Arms Up

The center of mass of the two arms is assumed to be at the subject's acromion level.

Figure 26. Positions of Arms

## Footwear

It is highly recommended that the test subjects do all exercises with the minimal possible footwear, ideally barefoot, to get the maximum possible acceleration values that can be archived under the different simulated gravity circumstances. However, the subjects should wear socks in order to prevent the sickness due to cold feet.

### 9.3 Calculations for angular velocities (in RPM) of the centrifuge

The angular velocity of the centrifuge for each subject was estimated by considering the comparable 1g at the center of mass of the subject's body at the midpoint of squats (the hip position is at midway between up and down position). The squat exercise workload on the centrifuge was expected to be comparable to that on the control station.

On the control station, the combined force of the two force plates should be equal to the mass of subject's body with equipment ( $M_{\text{BodyWithEquipment}}$ ) multiplied by 1g ( $9.81\text{m/s}^2$ ).

On the centrifuge, 1g was expected to be at the center of mass of the subject's body at midpoint position with the masses of the equipment and the sled. Then, the force from the mass of the sled was compensated by adjusting the angular velocity of the centrifuge ( $\omega_{\text{Centrifuge}}$ ). The  $\omega_{\text{Centrifuge}}$  from the unit of radians per second can be converted to the unit of round per minute (RPM) by this formula:  $\omega_{\text{Centrifuge}} = \text{RPM} \times 2\pi / 60$ .

Since the force plates on the centrifuge include forces from their own mass (30kg for two plates),

At radius 3.5m, the combined force of the two force plates should be read as:

$$\begin{aligned} &= ( M_{\text{BodyWithEquipment}} \times 9.81 ) + ( M_{\text{TwoForcePlates}} \times R \times (\omega_{\text{Centrifuge}})^2 ) \\ &= ( M_{\text{BodyWithEquipment}} \times 9.81 ) + ( M_{\text{TwoForcePlates}} \times 3.5 \times \text{RPM}^2 \times 4\pi^2 / 3600 ) \\ &= ( M_{\text{BodyWithEquipment}} \times 9.81 ) + ( 30 \times 3.5 \times \text{RPM}^2 \times \pi^2 / 900 ) \end{aligned}$$

At radius 2.5m, the combined force of the two force plates should be read as

$$= ( M_{\text{BodyWithEquipment}} \times 9.81 ) + ( 30 \times 2.5 \times \text{RPM}^2 \times \pi^2 / 900 )$$

## 9.4 Subject selection

Number of subjects: 8 (4 males and 4 females) will partake in this study.

### Inclusion criteria

- Subjects aged 20-50 with no relevant medical or mental history
- Height between 1.58 and 1.90 m
- Weight between 50 and 100 kg
- BMI between 18 and 28
- Negative medical screening examination
- Normotensive
- No history of orthostatic hypotension associated with for example Addison's disease or some antidepressants
- Able of hearing and sight
- Ability to comprehend and consent to the risks associated with the study
- Negative pregnancy test for females
- Signed informed consent form and contract

### Exclusion Criteria

- Bone fractures that are still being treated, i.e. in a cast
- Past bone fractures of the legs, hips or spine which are deemed too unstable by the examining physician
- Injures of the knee, hips or spine
- Diseases of the musculoskeletal system that impair muscle function
- Diabetes type I and II
- History of motion sickness
- Smokers including smokers that quit less than 6 months ago
- The examining physician is free to exclude any participant for reasons not necessarily listed here

### Drop-out reasons

- Request by subject for any reason whatsoever, without the need for justification
- Any evidence for adverse effects that cannot justify the continued participation in the study

## 9.5 Body Measurements

Based on Yeadon human body model, the body segments of each test subject were measured by a measuring tape and a measuring ruler. Perimeters, widths and segment lengths of arm part, leg part and torso part of the eight subjects were measured as shown on the data table of appendix B. Then, the data were used as inputs into the MICRO-G Inertia software developed by Rebecca Sampson and Rachel Ellman at the Massachusetts Institute of Technology in July 2005. This software is based on the paper "The Simulation of Aerial Movement - II. A Mathematical Inertia Model of the Human Body" by M.R. Yeadon. It calculated mass, length and center of mass of each body segment and store the output data as .mat file on MATLAB, which was very convenient for the data processing method. The detailed results of the masses, lengths and centers of masses of body segments of the eight subjects are shown on appendix C.



Figure 27. Body Measurements and Calculations using the MICRO-G Inertia software

### Foot Elevation

Foot elevation is length measured when a test subject squats downward to a knee angle of 90° and the tip of toes is at the same vertical line as the knee (shown on figure 28). Each test subject has different foot elevation.



Figure 28. Foot Elevation Measurement

The main data and measurements of the eight subjects are shown on table 6, which subject N was the only subject who used the extra pillow. The masses of subjects calculated by the MICRO-G Inertia software using the body measurements data were deviated from the body weights (without equipment) measured on the weight scale on the experiment date, but the differences were less than 3% of the body weights.

**Table 6. List of Test Subjects**

No.	Subj. ID	Age	Gender	Height (m)	Body Weight from Measurement (kg)	Mass of Subject calculated by the MICRO-G Inertia software (kg)	Foot elevation (m)	CM Sled from Top of Head (m)	CM Pillow from Top of Head (m)	Pillow Mass (kg)	RPM at 3.5m Radius	RPM at 2.5m Radius
1	A	28	Female	1.71	64.3	64.5224	0.24	0.64	-	-	17.32	21.86
2	C	22	Female	1.70	60.9	61.1502	0.25	0.60	-	-	17.18	21.58
3	N	28	Female	1.6	57.8	56.6945	0.24	0.46	0.17	0.5	16.00	20.00
4	P	24	Female	1.72	63.2	63.3611	0.32	0.66	-	-	17.20	21.63
5	F	27	Male	1.72	69.1	69.8349	0.28	0.64	-	-	17.20	21.63
6	H	26	Male	1.79	94.5	91.9000	0.30	0.63	-	-	17.30	21.90
7	R	35	Male	1.85	84.6	84.9186	0.24	0.67	-	-	17.42	22.05
8	S	29	Male	1.75	75.4	74.9487	0.25	0.66	-	-	17.25	21.73

## 9.6 Statistics Method

### Pearson Product-Moment Correlation

The Pearson product-moment correlation coefficient is a measure of the strength of a linear association between two variables and is denoted by  $r$ . Basically, a Pearson product-moment correlation attempts to draw a line of best fit through the data of two variables, and the Pearson correlation coefficient,  $r$ , indicates how far away all these data points are to this line of best fit. It ranges from -1.0 to +1.0. The closer  $r$  is to +1 or -1, the more closely the two variables are related. If  $r$  is close to 0, it means there is no relationship between the variables. If  $r$  is positive, it means that as one variable gets larger the other gets larger. If  $r$  is negative it means that as one gets larger, the other gets smaller (often called an inverse correlation) [14].

It is obtained by dividing the covariance of the two variables by the product of their standard deviations. The sample correlation coefficient is written as:

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{n s_x s_y} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

where  $\bar{x}$  and  $\bar{y}$  are the sample means of X and Y, and  $s_x$  and  $s_y$  are the sample standard deviations of X and Y [15].

In MATLAB, the `corr` function (by default) was used to find the Pearson's linear correlation coefficient that can be written as: `[RHO,PVAL] = corr (X,Y, 'tail', 'right')`

where PVAL is a matrix of p-values for testing the hypothesis of no correlation against the alternative that there is a nonzero correlation. Each element of PVAL is the p value for the corresponding element of RHO. If PVAL is small, say less than 0.05, then the correlation RHO is significantly different from zero. Moreover, the right tail is for testing the hypothesis of correlation greater than zero.

Besides, in this study, the standard normal distribution method on MATLAB was used to find the mean and the standard deviation of the differences between the calculated knee position values and the real data values, and the differences between the calculated foot reaction force values and the real data values. The differences are the absolute values of the calculated values minus the real data values.

Standard error is the standard deviation of the sampling distribution of the mean. The standard error of a sample depends on the sample size and the larger the size of sample the smaller the standard error. In sample statistics, standard error is computed by dividing the sample standard deviation by the square root of the size of sample (the total count of numbers). The samples standard deviation is computed by taking square root of the sum of squared differences between the variables and the mean divided by one less than the total count of numbers in the data set [16].

$$s_e = \frac{s_{sd}}{\sqrt{n}} \quad \text{where} \quad s_{sd} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \mu)^2} \quad \text{and} \quad \mu = \frac{1}{n} \sum_{i=1}^n x_i$$

$s_{sd}$  is the sample standard deviation of a data set

$\mu$  is the mean of a data set

$X_i$  is the variable at the  $i$  index of a data set

$n$  is the total count of numbers in a data set

## Chapter 10. Results

MATLAB is used to calculate the biomechanical and math models, develop the simulation, extract, process, and analyze the collected data, and plot the results.

### 10.1 Data processing and analysis

From the Vicon motion capturing system, there are two main types of data files that were used for the calculations: markers data (.c3d) and analog signals data (.CSV). The markers of each motion capturing file were labeled on the Vicon system of the centrifuge and of the control station (as shown on figures 29, 30, and 31). The data were primarily processed on the Vicon system, and then, transferred to further processed, analyzed, and calculated on MATLAB. The markers that were mainly used for the calculations are left and right hip markers, as well as left and right knee markers that were used for comparing and checking the calculation results. Moreover, the analog signals data that were used for comparing and checking the calculation results include forces from left and right force plates (in unit of Newton), sled positions (in unit of voltage), and squat profile signals (in unit of voltage).

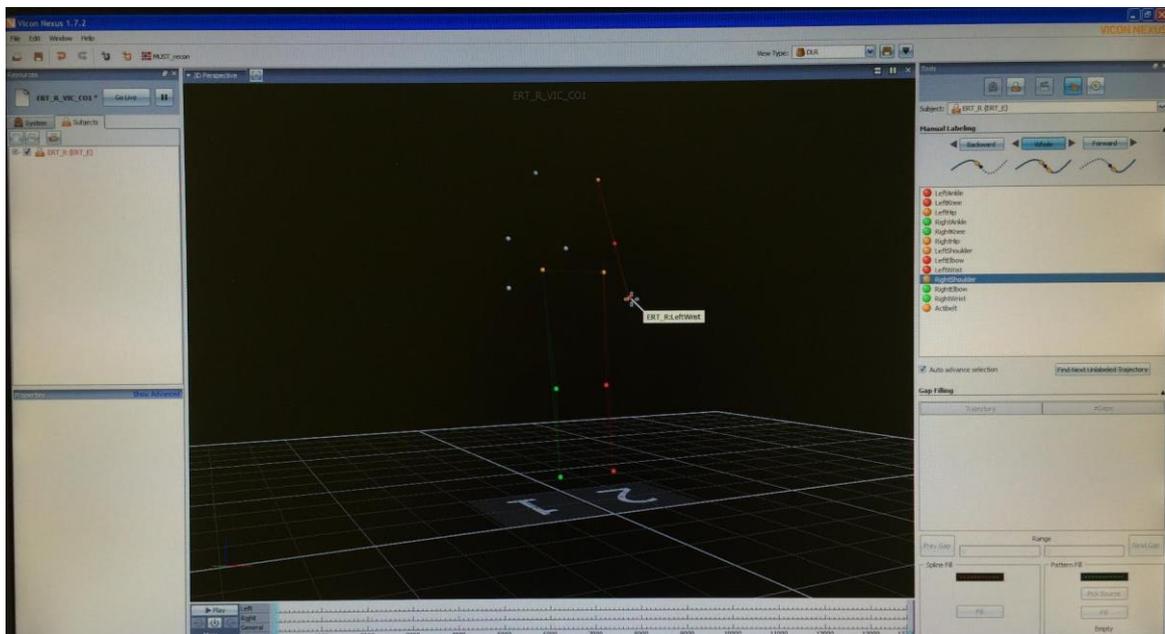


Figure 29. Labeling the markers on the Vicon system of the control station

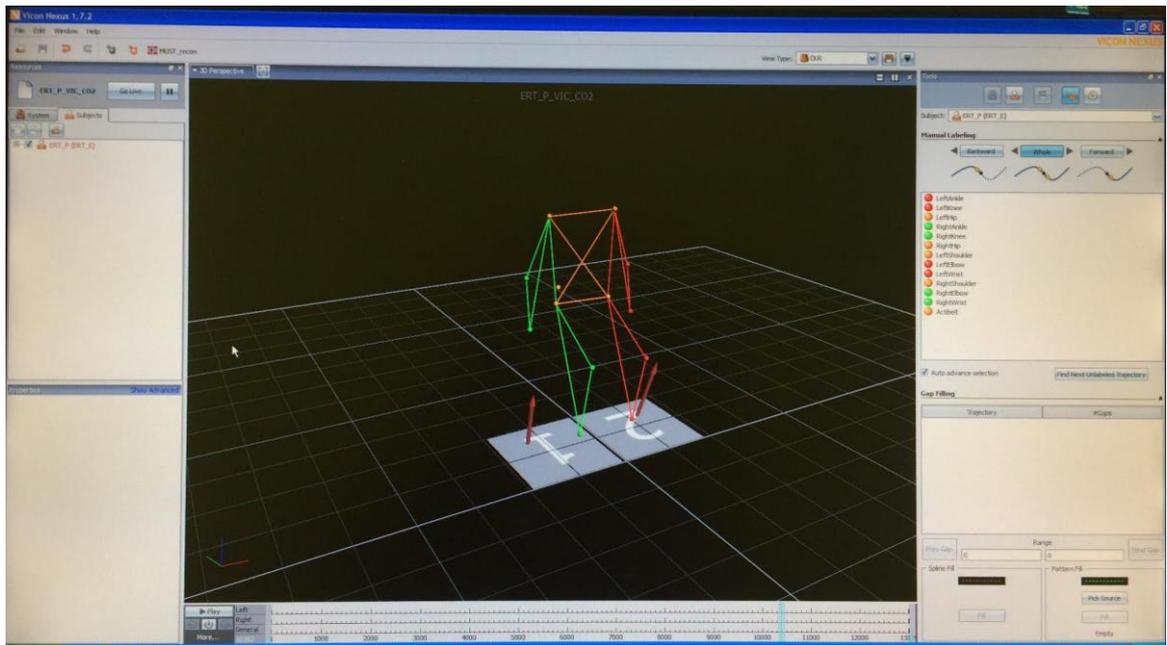


Figure 30. The markers that were labeled on the Vicon system of the control station

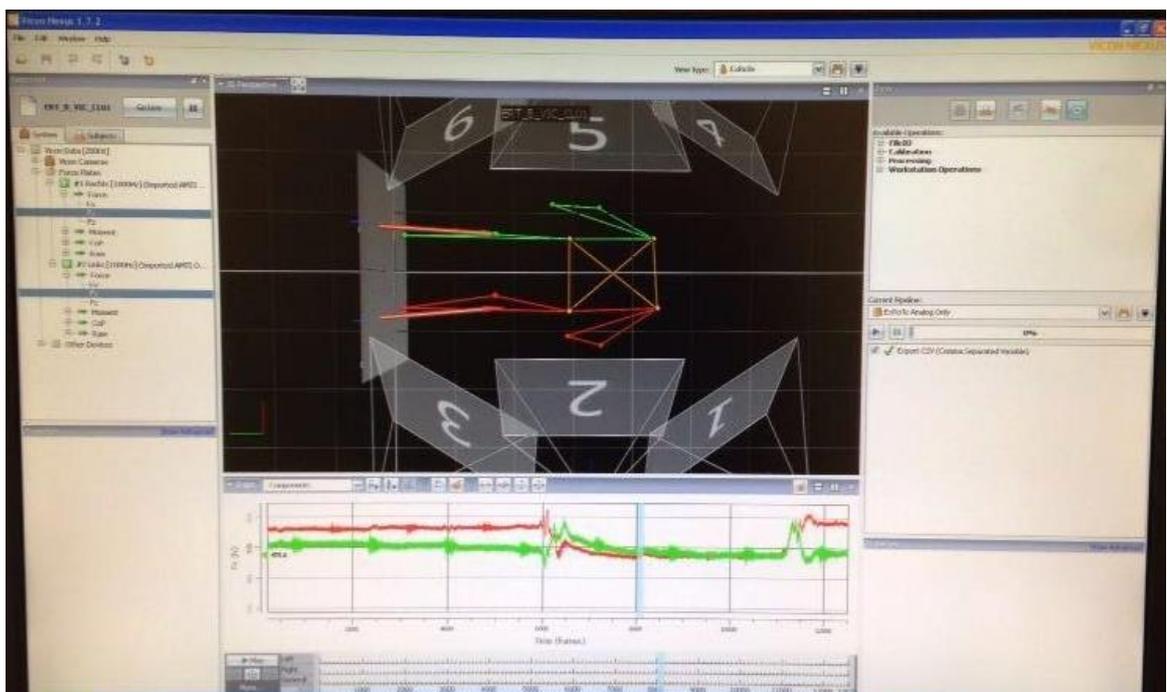


Figure 31. The markers that were labeled on the Vicon system of the centrifuge

Using MATLAB, the graph of the squat profile signal, that was shown on the motivation tool monitor to the subject, was plotted in comparison with the graph of the sled position that the subject performed in reality. As we can see on figure 32 and figure 33, in real squat practice, the subjects could not perform squatting at the constant speed with the sharp turns as same as they saw on the monitor. The graphs of the real performances include curves at the turning points, which means the motions were not in the constant velocity, but in various velocities according to different accelerations of the body parts at different positions.

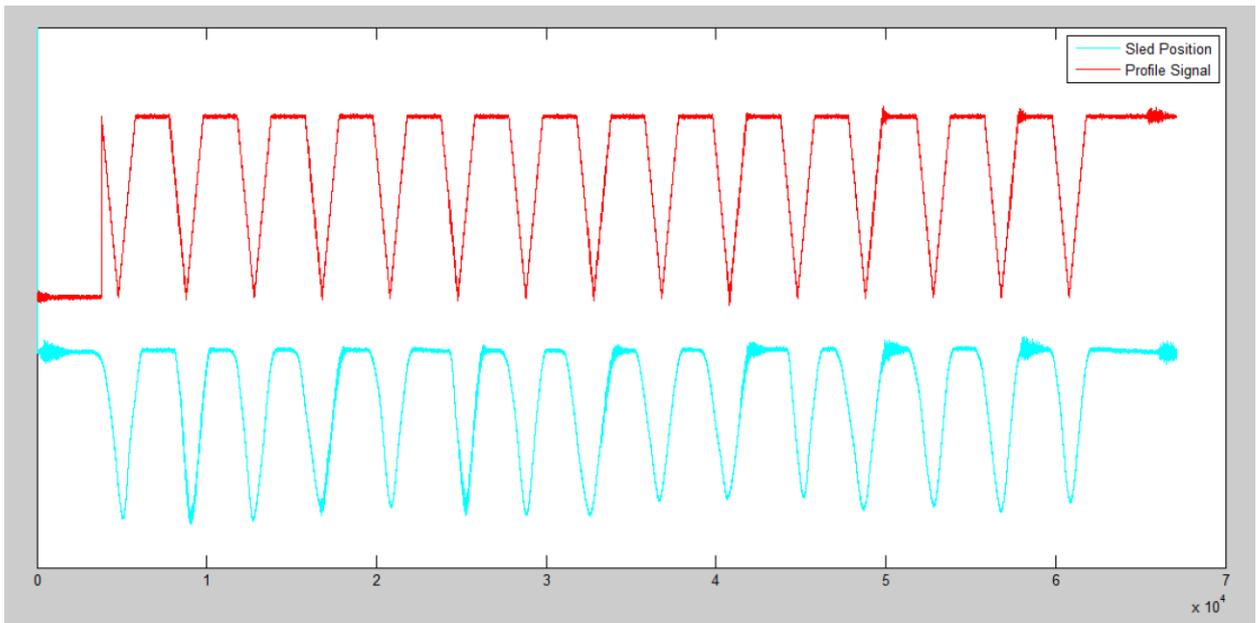


Figure 32. Comparison between the squat profile signal 1 and the sled position signal of subject C

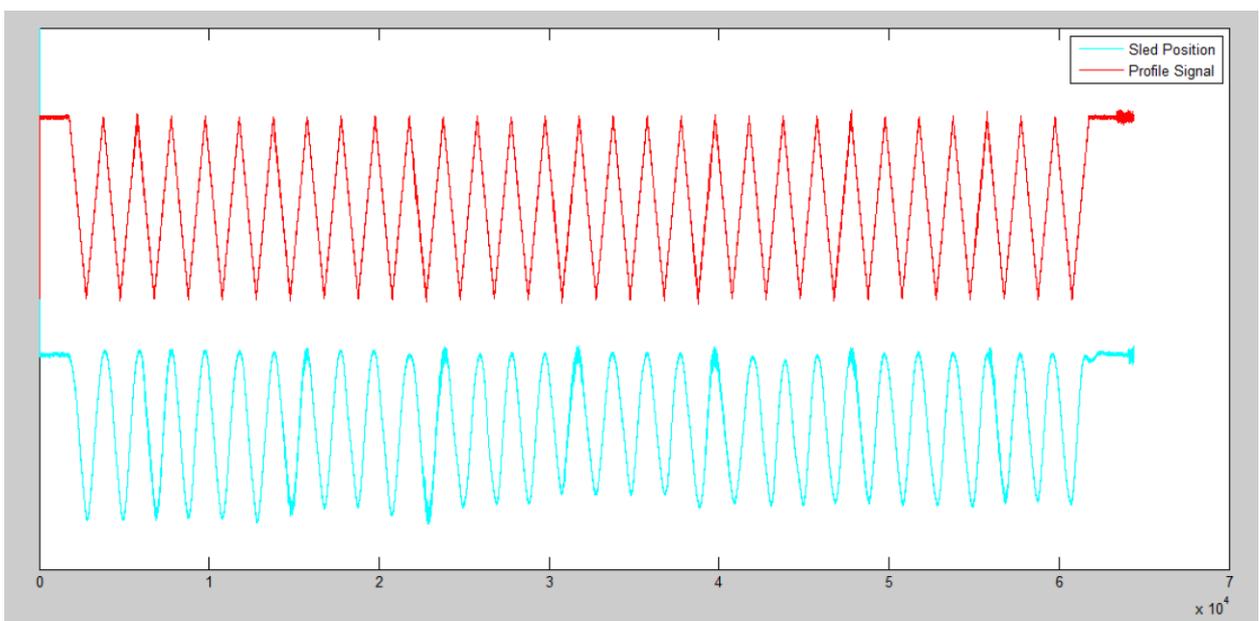


Figure 33. Comparison between the squat profile signal 2 and the sled position signal of subject C

The sampling size of both of the markers data file and the analog signals data file is 200 frames per second (200 Hz in frequency), but the analog signals data file always presents in sub-frames, which one frame includes 5 sub-frames. Thus, plotting the markers data and the analog signals data on the same graph requires us to resample 1 sub-frame out of the 5 sub-frames from each frame of the analog signals data. In order to check whether the markers data file and the analog signals file are synchronized, the sled positions and the hip markers positions were displayed on the same plot (figure 34). We can see that they are synchronized with the same amplitude, however, the sled position data has slightly more noises.

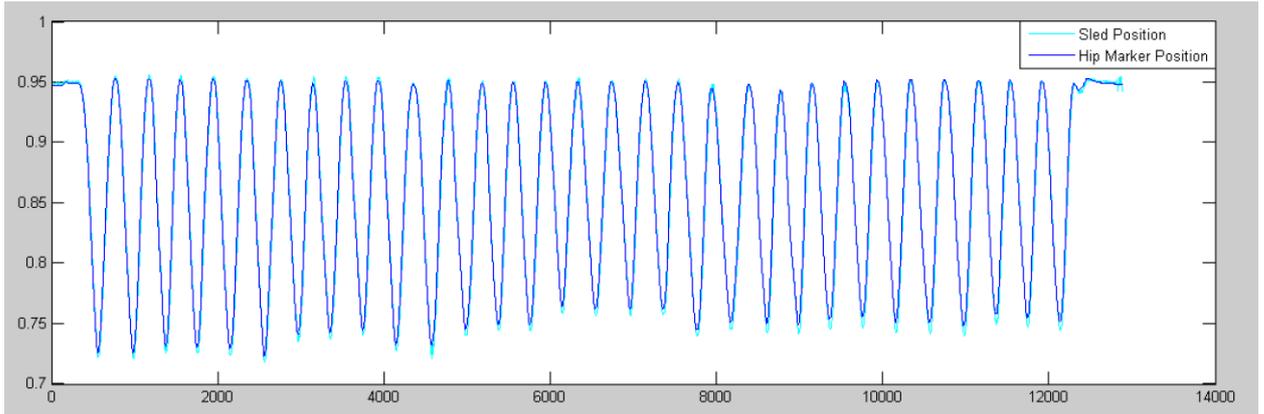


Figure 34. Comparison between the sled positions and the hip marker positions of subject C

Furthermore, the data of foot reaction forces on the left and the right force plates were combined. Since the forces from the force plates on the centrifuge include the forces generated by their own mass (30kg for two plates), the combined forces needed to be subtracted by of the forces generated by the mass of the force plates, which is equal to  $m_{ForcePates}(\omega_{Centrifuge})^2R$ , where the mass of the two force plates ( $m_{ForcePates}$ ) is 30 kg, the radius from the center of rotation of the centrifuge to the force plates ( $R$ ) is either 3.5 m or 2.5 m, and the angular velocity of the centrifuge ( $\omega_{Centrifuge}$ ) is different from one subject to another subject. However, the forces from the force plates on the control station do not include the forces generated by their own mass, so we could use the combined forces directly.

Besides, in order to reduce some noises from the data of forces, the smooth function on MATLAB was used to smoothen the forces. This function smoothes the data using a moving average filter, the lowpass filter with filter coefficients equal to the reciprocal of the span (the default span is 5). As shown on figure 35, the smoothened forces of subject C are cleaner and better representing the data than the raw data of the forces.

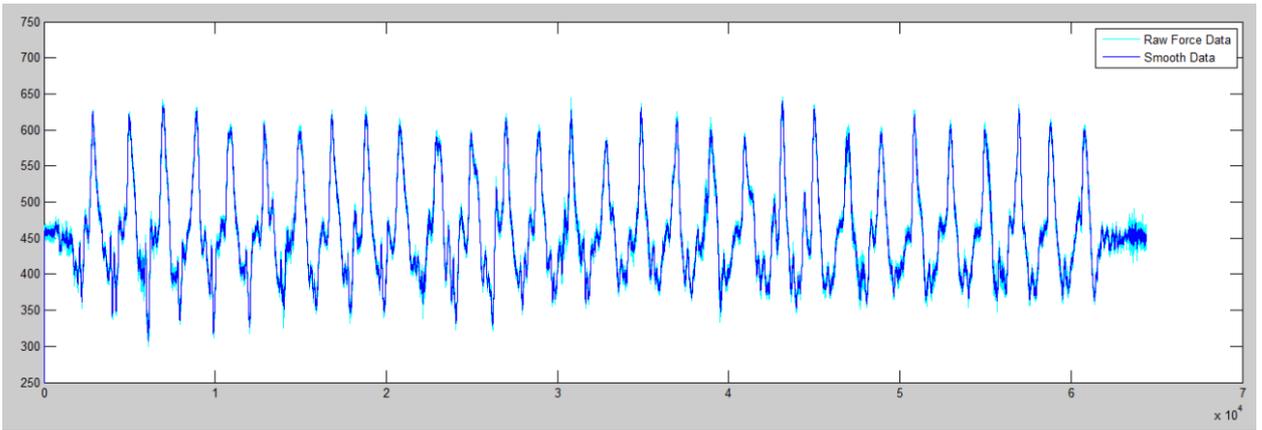


Figure 35. Comparison between the raw data of the forces and the smoothed forces of subject C

### Obtaining hip velocities and hip accelerations from positions of the hip marker

After getting the hip positions from the hip marker file, in order to get the velocities and the accelerations of the hip, the Smoothing Spline model of fit curve function on MATLAB was used to fit a smoothing spline curve through hip marker variables and return goodness of fit information and the output structure as shown on figure 36. The output structure also includes the first derivative of the curve. This means we can directly get the hip velocities (the first derivative of the hip positions) from fitting the hip marker graph with a smoothing spline curve. Then, likewise, we can directly get the hip accelerations (the first derivative of the hip velocities) from fitting the hip velocity graph with another smoothing spline curve as shown on figure 37 and figure 38. The approach to obtain the velocities and the accelerations of the hip can be concluded into five following steps:

- Step 1: Fit the hip marker (position) graph with a smoothing spline curve.
- Step 2: Get the velocity parameters from Step 1.
- Step 3: Fit the velocity parameters from Step 2 with another smoothing spline curve.
- Step 4: Get the acceleration parameters from Step 3.
- Step 5: Smooth the hip velocity from Step 2 and the hip acceleration from Step 4.

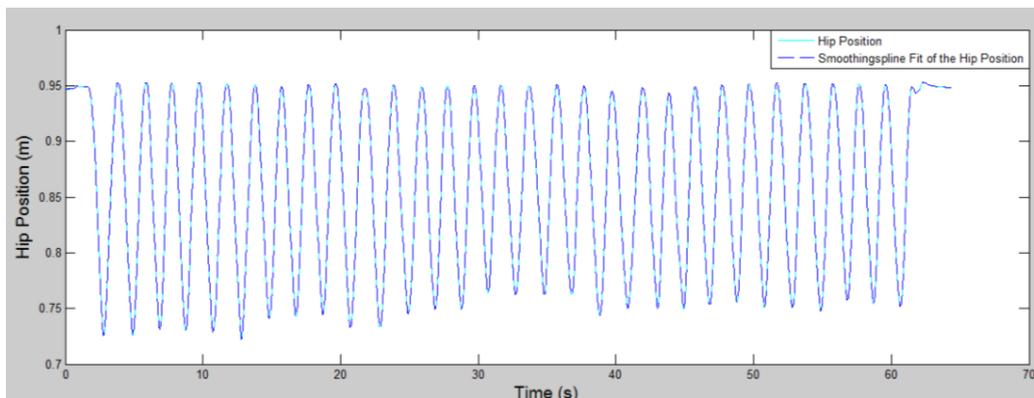


Figure 36. Fitting the hip marker graph of subject C with a smoothing spline curve

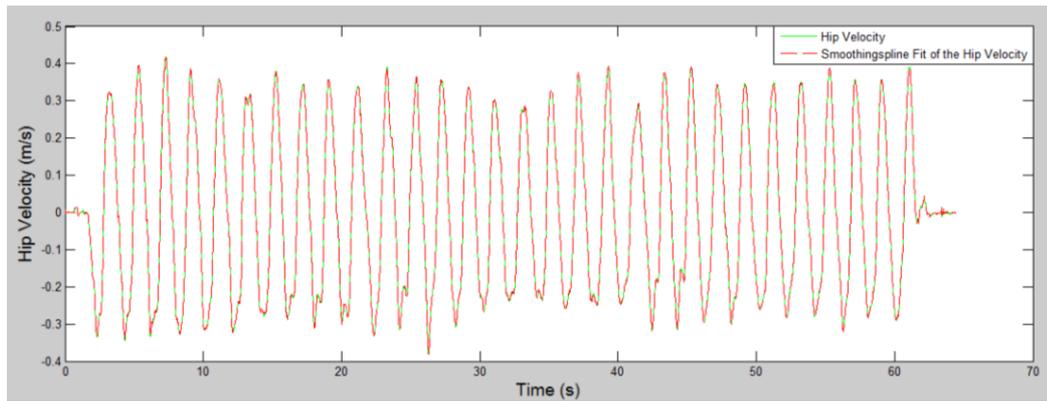


Figure 37. Fitting the hip velocity parameters of subject C with a smoothing spline curve

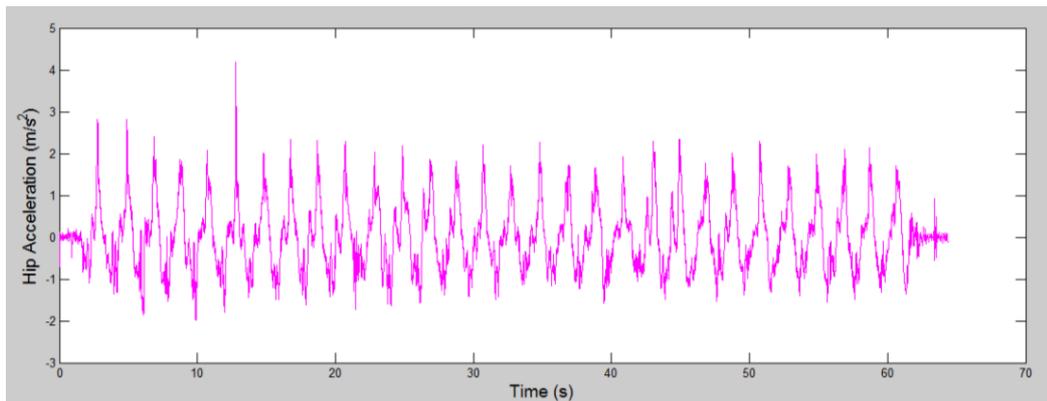


Figure 38. Hip accelerations of subject C obtaining from fitting the hip velocity with a smoothing spline curve

In order to check the correction of the obtained hip accelerations, the y-component of the acceleration data from the accelerometer attached to the waist of the subject C was plotted on figure 39 for comparison. The magnitude and the pattern of the accelerations from the accelerometer were similar to those of the hip accelerations obtained from processing data of the hip marker.

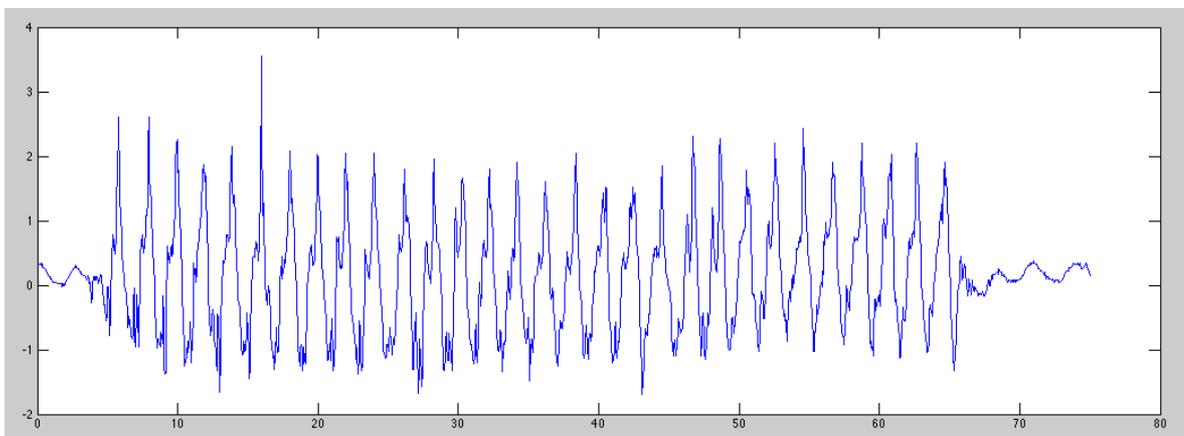


Figure 39. Hip accelerations of subject C from the accelerometer attached on the waist of the subject

## 10.2 Results from Static Postures

The static posture experiment on the centrifuge consists of 6 combinations of body positions and arms positions:

Part 1) Body at up position with both arms downward to the feet

Part 2) Body at up position with both arms on chest

Part 3) Body at up position with both arms up (on head)

Part 4) Body at down position with both arms downward to the feet

Part 5) Body at down position with both arms on chest

Part 6) Body at down position with both arms up (on head)

### Subject P

Figure 40 shows the result of the experiment of subject P on the centrifuge with the radius of 3.5 m, the combined foot reaction forces of the two force plates (subtracted the forces due to the mass of the plates) were plotted in cyan color with the mean values of each part in dark blue color. The predicted forces from the calculation model (assuming that the positions of hip at up and down positions were constant) were plotted in green color and the calculated forces from the real hip marker positions were plotted in red color. The predicted forces and the calculated forces are exactly the same at part 1, part 2 and part 3, and slightly different at part 4, part 5 and part 6. However, the predicted forces and the calculated forces are obviously lower than the mean of the real forces. The differences between the predicted forces and the real forces were presented as dP1, dP2, dP3, dP4, dP5, and dP6. Moreover, the forces when the body was at down position (part 4, 5, and 6) are much more than the forces when the body was at up position (part 1, 2, and 3). In addition, with the same body position, the forces were reduced from when the arms were placed downward by moving the arms upward to be on the chest and up on the head respectively.

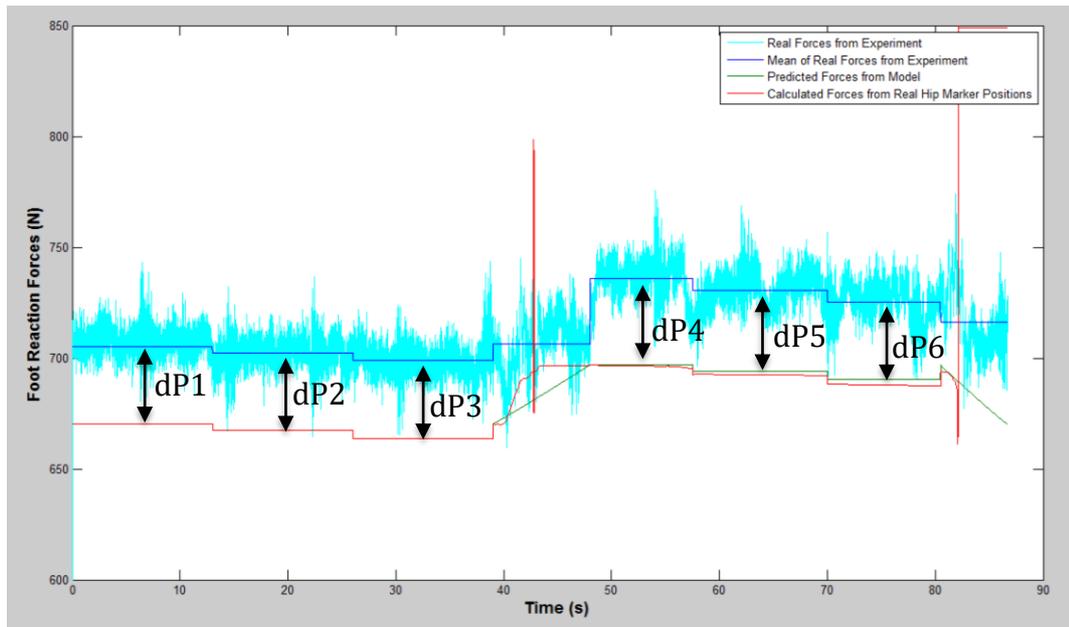


Figure 40. Comparison between the real data of the forces and the predicted forces of subject P during static postures on the centrifuge with the radius of 3.5m

From the computation,  $dP1 = 34.8290$  N,  $dP2 = 34.8590$  N,  $dP3 = 35.2191$  N,  $dP4 = 38.9224$  N,  $dP5 = 36.5191$  N, and  $dP6 = 35.0441$  N. The mean value of these dPs is equal to 35.8988 N. The differences of the force values might be caused by many reasons such as some technical problems or noise signals of the force plates, and/or the additional forces by fluid shifts or muscle activities from the internal body parts. However, if it was caused only by the fluid shifts from the upper body to the feet of the subject, this following formula could be used to compute the portion ( $k$ ) of the fluid shift from the body mass of the subject:

$$k \cdot m_{Body}(\omega_{Centrifuge})^2 R = \text{Mean of the differences of the forces} = 35.8988$$

where the body mass ( $m_{Body}$ ) of subject P is 63.2 kg,  $R$  is 3.5m,

and  $\omega_{Centrifuge} = 17.2$  rpm = 1.8012 rad/s.

As a result,  $k = 0.05$ . This means the fluid shift of subject P during the centrifugation approximately 5% of the body mass of subject P.

After adding the additional forces due to the fluid shift to the predicted forces and the calculated forces on figure 40, the new adjusted forces on figure 41 (in green color) show the better fit to the real data of forces.

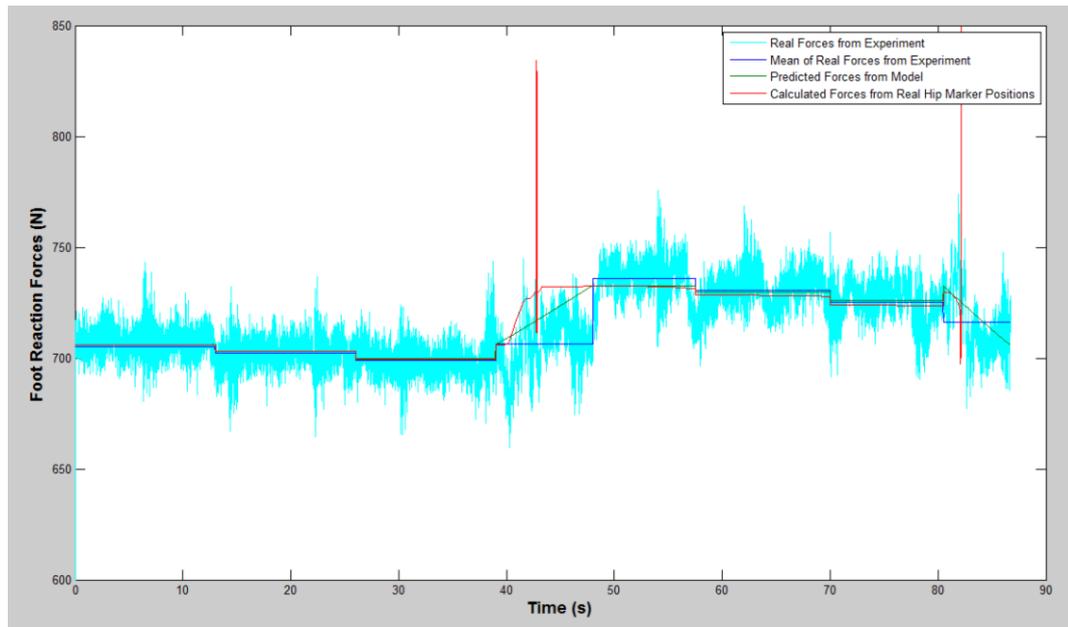


Figure 41. Comparison between the raw data of the forces and the adjusted forces of subject P during static postures on the centrifuge with the radius of 3.5m

## Subject H

Applying the similar process to the experiment of subject H on the centrifuge with the radius of 2.5 m, the results are shown on figure 42, which the predicted forces and the calculated forces are quite the same at part 1, part 2 and part 3, and slightly different at part 4, part 5 and part 6. However, the predicted forces and the calculated forces are obviously lower than the mean of the real forces. The differences between the predicted forces and the real forces were presented as dH1, dH2, dH3, dH4, dH5, and dH6. Moreover, the forces when the body was at down position (part 4, 5, and 6) are much more than the forces when the body was at up position (part 1, 2, and 3). In addition, with the same body position, the forces were reduced from when the arms were placed downward by moving the arms upward to be on the chest and up on the head respectively. From the computation, dH1 = 73.8 N, dH2 = 68.3968 N, dH3 = 67.1751 N, dH4 = 57.1514 N, dH5 = 56.9188 N, and dH6 = 57.9021 N. The mean value of these dHs is equal to 63.5574 N.

The differences of the force values might be caused by many reasons such as some technical problems or noise signals of the force plates, and/or the additional forces by fluid shifts or muscle activities from the internal body parts. However, if it was caused only by the fluid shifts from the upper body to the feet of the subject, this following formula could be used to compute the portion ( $k$ ) of the fluid shift from the body mass of the subject:

$$k \cdot m_{Body}(\omega_{Centrifuge})^2 R = \text{Mean of the diffrences of the forces} = 63.5574$$

where the body mass ( $m_{Body}$ ) of subject H is 94.5 kg,  $R$  is 2.5m,

and  $\omega_{Centrifuge} = 21.9 \text{ rpm} = 2.2934 \text{ rad/s}$ .

As a result,  $k = 0.0511$ . This means the fluid shift of subject H during the centrifugation approximately 5% of the body mass of subject H. After adding the additional forces due to the fluid shift to the predicted forces and the calculated forces on figure 42, the new adjusted forces on figure 43 (in green color) show the better fit to the real data of forces.

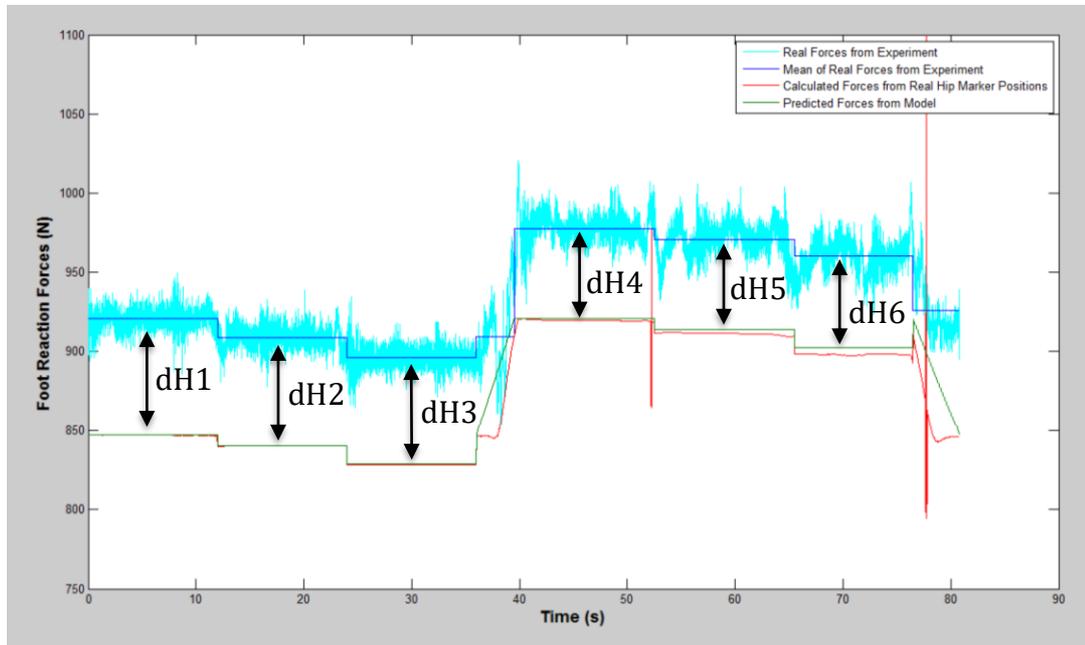


Figure 42. Comparison between the real data of the forces and the predicted forces of subject H during static postures on the centrifuge with the radius of 2.5m

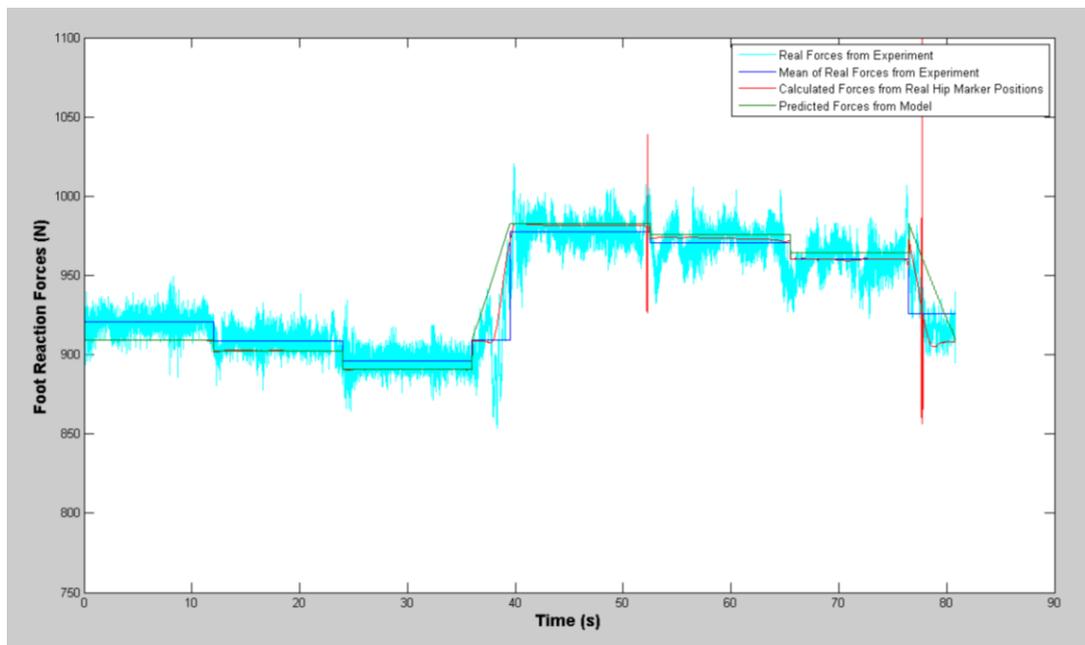


Figure 43. Comparison between the real data of the forces and the adjusted forces of subject H during static postures on the centrifuge with the radius of 2.5m

## Subject A

Applying the similar process to the experiment of subject A on the centrifuge with the radius of 2.5 m, the results are shown on figure 44, which the predicted forces and the calculated forces are quite the same at all parts. However, the predicted forces and the calculated forces are obviously lower than the mean of the real forces at part 1, part 2, and part 3, but surprisingly much higher than the mean of the real forces at part 4, part 5, and part 6. This is because subject A was the first subject and the experiment operator did not concern about the problem of the subject moves the body too low, in which the edge of the sled bump to the end of the sled track on the centrifuge. Thus, the forces of the subject's body during centrifugation at down position were distributed to the end of the sled track, not only to the subject's feet on the force plates as expected. However, this is one of the lesson learns for the other experiments that there should be some gap between the edge of the sled and the end of the sled track and the subjects should also be informed to perform correctly on the centrifuge.

The differences between the predicted forces and the real forces during up position were presented as  $dA_1$ ,  $dA_2$ , and  $dA_3$ . From the computation,  $dA_1 = 40.2231$  N,  $dA_2 = 43.9740$  N, and  $dA_3 = 43.5294$  N. The mean value of these  $dA_s$  is equal to 42.5755 N.

The differences of the force values might be caused by many reasons such as some technical problems or noise signals of the force plates, and/or the additional forces by fluid shifts or muscle activities from the internal body parts. However, if it was caused only by the fluid shifts from the upper body to the feet of the subject, this following formula could be used to compute the portion ( $k$ ) of the fluid shift from the body mass of the subject:

$$k \cdot m_{Body}(\omega_{Centrifuge})^2 R = \text{Mean of the differences of the forces} = 42.5755$$

where the body mass ( $m_{Body}$ ) of subject A is 64.3 kg,  $R$  is 2.5m, and  $\omega_{Centrifuge} = 21.86$  rpm = 2.2892 rad/s.

As a result,  $k = 0.0505$ . This means the fluid shift of subject A during the centrifugation approximately 5% of the body mass of subject A. After adding the additional forces due to the fluid shift to the predicted forces and the calculated forces on figure 44, the new adjusted forces on figure 45 (in green color) show the better fit to the real data of forces.

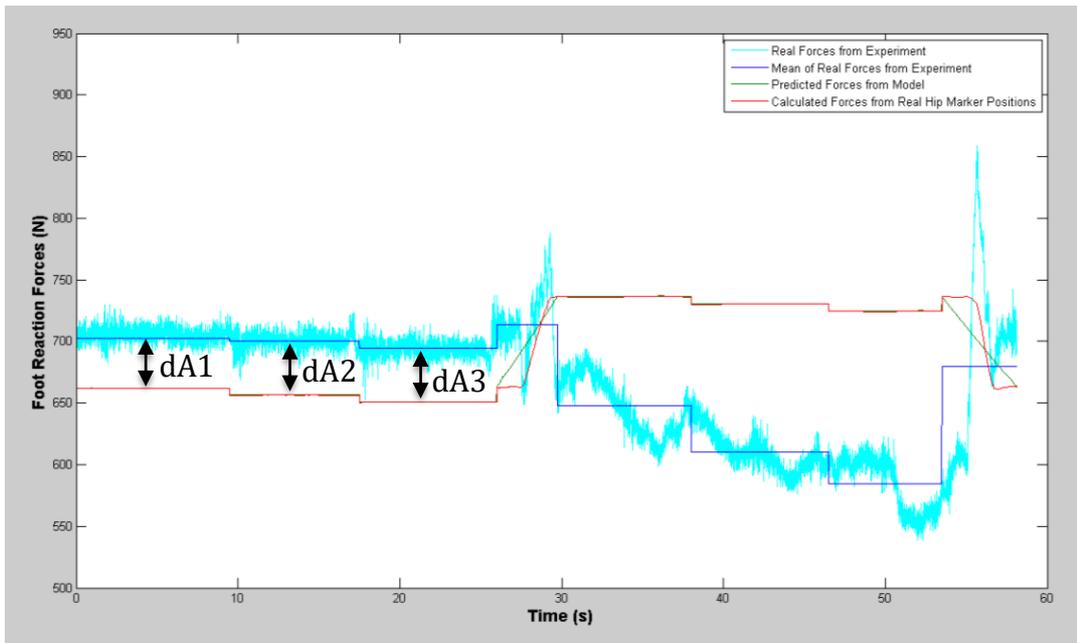


Figure 44. Comparison between the raw data of the forces and the predicted forces of subject A during static postures on the centrifuge with the radius of 2.5m

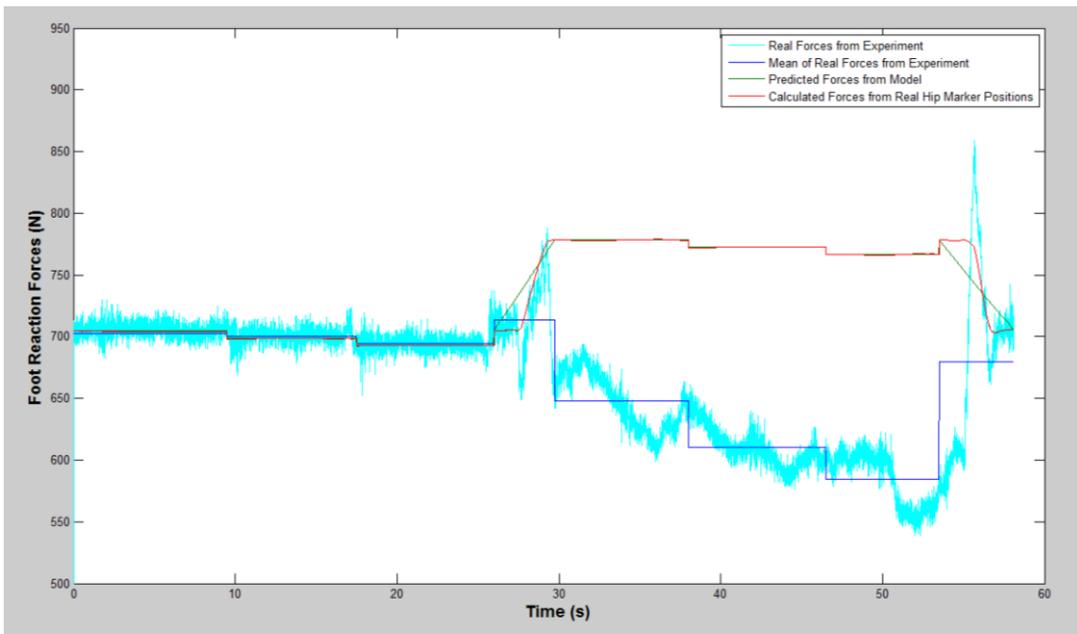


Figure 45. Comparison between the raw data of the forces and the adjusted forces of subject A during static postures on the centrifuge with the radius of 2.5m

### 10.3 Statistics Results

Since the sample rate of the marker on Vicon System is 200Hz (= 200 frames per second), for the comparable results, the data were cropped for 10 seconds or 2000 marker frames. The comparison between the calculated knee position values and the real data values, and the comparison between the calculated foot reaction force values and the real data values are shown in the following tables.

**Table 7. Statistics results of subject A**

Subject A					Knee Positions				Foot Reaction Forces			
No.	Ref. Hip Marker File Name	From Frame To Frame	Position of Arms	Selected Hip Marker	Correlation		Differences		Correlation		Differences	
					Corr. Coeff. (r)	P value	Mean ( $\mu$ )	STD ( $S_{sd}$ )	Corr. Coeff. (r)	P value	Mean ( $\mu$ )	STD ( $S_{sd}$ )
1	ERT_A_VIC_CL03	1000 - 3000	Arms Down	Left Hip	0.9693	0	0.0081	0.0042	0.8784	0	43.0535	31.6463
2	ERT_A_VIC_CL03	5000 - 7000	Arms on Chest	Left Hip	0.9252	0	0.0058	0.0063	0.8964	0	45.6825	32.5954
3	ERT_A_VIC_CL03	9000 - 11000	Arms Up	Left Hip	0.9529	0	0.0053	0.0037	0.8990	0	49.6172	36.5998
4	ERT_A_VIC_CL02	1000 - 3000	Arms Down	Left Hip	0.8996	0	0.0061	0.0062	0.7772	0	42.0672	34.3233
5	ERT_A_VIC_CL02	5000 - 7000	Arms on Chest	Left Hip	0.8951	0	0.0057	0.0038	0.7957	0	44.0467	31.6722
6	ERT_A_VIC_CL02	9000 - 11000	Arms Up	Left Hip	0.8755	0	0.0054	0.0036	0.8485	0	41.3129	26.7393
7	ERT_A_VIC_CS03	1000 - 3000	Arms Down	Right Hip	0.9616	0	0.0095	0.0049	0.8964	0	51.5796	42.1824
8	ERT_A_VIC_CS03	5000 - 7000	Arms on Chest	Right Hip	0.9543	0	0.0088	0.0046	0.9023	0	55.4037	48.9166
9	ERT_A_VIC_CS03	9000 - 11000	Arms Up	Right Hip	0.9387	0	0.0088	0.0046	0.9095	0	62.8570	49.9407
10	ERT_A_VIC_CS02	1000 - 3000	Arms Down	Right Hip	0.8285	0	0.0064	0.0036	0.8212	0	55.3616	37.7657
11	ERT_A_VIC_CS02	5500 - 7500	Arms on Chest	Right Hip	0.7239	0	0.0080	0.0034	0.8481	0	53.3125	34.3085
12	ERT_A_VIC_CS02	10000 - 12000	Arms Up	Right Hip	0.7741	0	0.0089	0.0040	0.8200	0	56.1218	43.7299
13	ERT_A_VIC_CO2	2000 - 4000	Arms Down	Right Hip	0.9705	0	0.0126	0.0109	0.8057	0	63.9171	46.0801
14	ERT_A_VIC_CO1	7000 - 9000	Arms Down	Right Hip	0.9688	0	0.0181	0.0087	0.7468	0	58.7953	36.0570
<b>Mean</b>					0.9027		0.0084		0.8461		51.6520	
<b>Standard Error</b>					0.2413		0.0022		0.2261		13.8046	

**Table 8. Statistics results of subject C**

Subject C					Knee Positions				Foot Reaction Forces			
No.	Ref. Hip Marker File Name	From Frame To Frame	Position of Arms	Selected Hip Marker	Correlation		Differences		Correlation		Differences	
					Corr. Coeff. (r)	P value	Mean ( $\mu$ )	STD ( $S_{sd}$ )	Corr. Coeff. (r)	P value	Mean ( $\mu$ )	STD ( $S_{sd}$ )
1	ERT_C_VIC_CL03	500 - 2500	Arms Down	Left Hip	0.9649	0	0.0109	0.0064	0.9173	0	29.6554	22.0788
2	ERT_C_VIC_CL03	5000 - 7000	Arms on Chest	Left Hip	0.9790	0	0.0090	0.0052	0.9221	0	26.5157	18.0052
3	ERT_C_VIC_CL03	9000 - 11000	Arms Up	Left Hip	0.9828	0	0.0091	0.0049	0.9244	0	26.9907	17.3116
4	ERT_C_VIC_CL02	500 - 2500	Arms Down	Right Hip	0.8113	0	0.0141	0.0053	0.8078	0	21.2875	23.6605
5	ERT_C_VIC_CL02	5000 - 7000	Arms on Chest	Right Hip	0.9289	0	0.0154	0.0048	0.8822	0	18.8680	15.9007
6	ERT_C_VIC_CL02	9000 - 11000	Arms Up	Right Hip	0.9166	0	0.0149	0.0043	0.8792	0	18.5123	15.2260
7	ERT_C_VIC_CS03	1000 - 3000	Arms Down	Left Hip	0.9629	0	0.0066	0.0036	0.9232	0	31.5102	19.1579
8	ERT_C_VIC_CS03	5500 - 7500	Arms on Chest	Left Hip	0.9853	0	0.0056	0.0033	0.9315	0	32.5494	17.7375
9	ERT_C_VIC_CS03	9000 - 11000	Arms Up	Left Hip	0.9791	0	0.0053	0.0027	0.9287	0	29.6097	16.1946
10	ERT_C_VIC_CS02	1000 - 3000	Arms Down	Right Hip	0.9504	0	0.0164	0.0029	0.8596	0	23.6012	17.9779
11	ERT_C_VIC_CS02	5000 - 7000	Arms on Chest	Right Hip	0.8919	0	0.0159	0.0033	0.8554	0	24.5534	17.5778
12	ERT_C_VIC_CS02	9000 - 11000	Arms Up	Right Hip	0.9029	0	0.0160	0.0031	0.8565	0	24.3196	17.0471
13	ERT_C_VIC_CO2	8000 - 10000	Arms Down	Left Hip	0.9953	0	0.0043	0.0029	0.7828	0	43.2456	29.2559
14	ERT_C_VIC_CO1	7000 - 9000	Arms Down	Left Hip	0.9882	0	0.0044	0.0022	0.7548	0	23.0079	22.3089
<b>Mean</b>					0.9457		0.0106		0.8733		26.7305	
<b>Standard Error</b>					0.2527		0.0028		0.2334		7.1140	

**Table 9. Statistics results of subject N**

Subject N					Knee Positions				Foot Reaction Forces			
No.	Ref. Hip Marker File Name	From Frame To Frame	Position of Arms	Selected Hip Marker	Correlation		Differences		Correlation		Differences	
					Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )	Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )
1	ERT_N_VIC_CL03	700 - 2700	Arms Down	Left Hip	0.7647	0	0.0272	0.0089	0.9349	0	29.4695	26.8476
2	ERT_N_VIC_CL03	5000 - 7000	Arms on Chest	Left Hip	0.8714	0	0.0284	0.0057	0.9410	0	27.1355	25.5804
3	ERT_N_VIC_CL03	9000 - 11000	Arms Up	Left Hip	0.8733	0	0.0291	0.0065	0.9333	0	28.5832	26.2654
4	ERT_N_VIC_CL02	1700 - 3700	Arms Down	Left Hip	0.8663	0	0.0246	0.0047	0.9024	0	37.2422	24.7927
5	ERT_N_VIC_CL02	5000 - 7000	Arms on Chest	Left Hip	0.8929	0	0.0256	0.0040	0.9006	0	32.1258	21.7742
6	ERT_N_VIC_CL02	9000 - 11000	Arms Up	Left Hip	0.7793	0	0.0233	0.0054	0.9163	0	28.6638	21.1764
7	ERT_N_VIC_CS03	1000 - 3000	Arms Down	Left Hip	0.7471	0	0.0257	0.0116	0.9596	0	27.0039	23.6517
8	ERT_N_VIC_CS03	6000 - 8000	Arms on Chest	Left Hip	0.6149	1.6599e-208	0.0221	0.0100	0.9643	0	22.9606	20.8351
9	ERT_N_VIC_CS03	10500 - 12500	Arms Up	Left Hip	0.8188	0	0.0229	0.0068	0.9617	0	22.9884	21.5507
10	ERT_N_VIC_CS02	900 - 2900	Arms Down	Left Hip	0.3831	3.6017e-71	0.0157	0.0085	0.9595	0	18.9589	14.8063
11	ERT_N_VIC_CS02	5000 - 7000	Arms on Chest	Left Hip	0.4263	2.3358e-89	0.0158	0.0112	0.9602	0	19.8936	15.8613
12	ERT_N_VIC_CS02	10500 - 12500	Arms Up	Left Hip	0.0989	4.6968e-06	0.0132	0.0163	0.9714	0	20.0945	14.5015
13	ERT_N_VIC_CO2	9000 - 11000	Arms Down	Left Hip	0.6254	9.3504 e-218	0.0357	0.0251	0.7647	0	66.4356	38.2749
14	ERT_N_VIC_CO1	10000 - 12000	Arms Down	Right Hip	0.5475	5.3194 e-157	0.0292	0.0201	0.7132	8.9237e-311	71.6475	44.4773
<b>Mean</b>					0.6650		0.0242		0.9131		32.3716	
<b>Standard Error</b>					0.1777		0.0065		0.2440		8.6517	

**Table 10. Statistics results of subject P**

Subject P					Knee Positions				Foot Reaction Forces			
No.	Ref. Hip Marker File Name	From Frame To Frame	Position of Arms	Selected Hip Marker	Correlation		Differences		Correlation		Differences	
					Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )	Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )
1	ERT_P_VIC_CL03	1000 - 3000	Arms Down	Left Hip	0.9083	0	0.0164	0.0053	0.9416	0	23.5498	17.5603
2	ERT_P_VIC_CL03	5000 - 7000	Arms on Chest	Left Hip	0.8768	0	0.0156	0.0051	0.9251	0	25.6766	16.3826
3	ERT_P_VIC_CL03	9500 - 11500	Arms Up	Left Hip	0.8033	0	0.0148	0.0053	0.9224	0	25.3756	17.1336
4	ERT_P_VIC_CL02	1000 - 3000	Arms Down	Left Hip	0.8492	0	0.0218	0.0077	0.9234	0	11.9656	13.3148
5	ERT_P_VIC_CL02	5000 - 7000	Arms on Chest	Left Hip	0.9351	0	0.0238	0.0074	0.9147	0	9.8779	10.9042
6	ERT_P_VIC_CL02	9000 - 11000	Arms Up	Left Hip	0.9142	0	0.0219	0.0065	0.9227	0	11.7892	12.5639
7	ERT_P_VIC_CS03	1000 - 3000	Arms Down	Right Hip	0.9322	0	0.0025	0.0028	0.8548	0	37.2739	28.5064
8	ERT_P_VIC_CS03	5000 - 7000	Arms on Chest	Right Hip	0.9788	0	0.0022	0.0015	0.8807	0	34.1954	22.9394
9	ERT_P_VIC_CS03	9000 - 11000	Arms Up	Right Hip	0.9462	0	0.0034	0.0025	0.9112	0	31.0456	18.7920
10	ERT_P_VIC_CS02	500 - 2500	Arms Down	Right Hip	0.9686	0	0.0053	0.0032	0.7721	0	35.8466	26.4690
11	ERT_P_VIC_CS02	5000 - 7000	Arms on Chest	Right Hip	0.9296	0	0.0077	0.0048	0.8154	0	23.1382	25.9155
12	ERT_P_VIC_CS02	9000 - 11000	Arms Up	Right Hip	0.9033	0	0.0088	0.0052	0.8655	0	19.7315	22.1105
13	ERT_P_VIC_CO2	8000 - 10000	Arms Down	Left Hip	0.8062	0	0.0081	0.0075	0.7491	0	75.5896	55.6542
14	ERT_P_VIC_CO1	7000 - 9000	Arms Down	Left Hip	0.7917	0	0.0067	0.0052	0.7103	3.6993e-307	77.4004	47.0494
<b>Mean</b>					0.8960		0.0114		0.8649		31.6040	
<b>Standard Error</b>					0.2395		0.0030		0.2312		8.4465	

**Table 11. Statistics results of subject F**

Subject F					Knee Positions				Foot Reaction Forces			
No.	Ref. Hip Marker File Name	From Frame To Frame	Position of Arms	Selected Hip Marker	Correlation		Differences		Correlation		Differences	
					Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )	Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )
1	ERT_F_VIC_CL03	1000 - 3000	Arms Down	Left Hip	0.9485	0	0.0029	0.0022	0.9230	0	28.9236	17.7419
2	ERT_F_VIC_CL03	6500 - 8500	Arms on Chest	Left Hip	0.8256	0	0.0037	0.0030	0.9309	0	28.7406	17.0996
3	ERT_F_VIC_CL03	9000 - 11000	Arms Up	Left Hip	0.9226	0	0.0040	0.0027	0.9103	0	32.4211	20.8053
4	ERT_F_VIC_CL02	2000 - 4000	Arms Down	Left Hip	0.3254	8.1906e-51	0.0096	0.0058	0.8876	0	17.6164	17.4444
5	ERT_F_VIC_CL02	6000 - 8000	Arms on Chest	Left Hip	0.4291	1.1694e-90	0.0086	0.0057	0.8856	0	17.8989	16.6378
6	ERT_F_VIC_CL02	11000 - 13000	Arms Up	Left Hip	0.6809	8.6466e-273	0.0055	0.0041	0.8714	0	23.6526	17.6974
7	ERT_F_VIC_CS03	1000 - 3000	Arms Down	Left Hip	0.6907	8.9350e-284	0.0059	0.0055	0.9382	0	34.0563	20.4360
8	ERT_F_VIC_CS03	6000 - 8000	Arms on Chest	Left Hip	0.5413	1.0623e-135	0.0068	0.0067	0.9249	0	39.9065	20.2995
9	ERT_F_VIC_CS03	10000 - 12000	Arms Up	Left Hip	0.7503	0	0.0052	0.0043	0.9313	0	34.8237	19.2803
10	ERT_F_VIC_CS02	1000 - 3000	Arms Down	Left Hip	-0.0448	0.9774	0.0165	0.0111	0.8931	0	22.3019	17.9383
11	ERT_F_VIC_CS02	5000 - 7000	Arms on Chest	Left Hip	-0.0675	0.9987	0.0163	0.0116	0.9146	0	25.7676	19.1014
12	ERT_F_VIC_CS02	9000 - 11000	Arms Up	Left Hip	0.0375	0.0470	0.0152	0.0106	0.9265	0	24.4265	17.1105
13	ERT_F_VIC_CO2	4000 - 6000	Arms Down	Left Hip	0.8778	0	0.0185	0.0200	0.8332	0	54.9065	34.8737
14	ERT_F_VIC_CO1	6000 - 8000	Arms Down	Left Hip	0.6451	6.4376e-236	0.0160	0.0111	0.8024	0	33.3204	33.6064
<b>Mean</b>					0.5402		0.0096		0.8981		29.9116	
<b>Standard Error</b>					0.1444		0.0026		0.2400		7.9942	

**Table 12. Statistics results of subject H**

Subject H					Knee Positions				Foot Reaction Forces			
No.	Ref. Hip Marker File Name	From Frame To Frame	Position of Arms	Selected Hip Marker	Correlation		Differences		Correlation		Differences	
					Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )	Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )
1	ERT_H_VIC_CL03	1500 - 3500	Arms Down	Right Hip	0.9293	0	0.0510	0.0023	0.9046	0	38.5445	34.9519
2	ERT_H_VIC_CL03	5000 - 7000	Arms on Chest	Right Hip	0.8846	0	0.0510	0.0029	0.9186	0	37.8434	30.0663
3	ERT_H_VIC_CL03	9000 - 11000	Arms Up	Right Hip	0.9154	0	0.0512	0.0031	0.9159	0	37.4203	33.7109
4	ERT_H_VIC_CL02	1000 - 3000	Arms Down	Right Hip	0.8437	0	0.0500	0.0035	0.8113	0	49.3567	41.1217
5	ERT_H_VIC_CL02	6000 - 8000	Arms on Chest	Right Hip	0.9458	0	0.0506	0.0017	0.8197	0	54.3550	36.3523
6	ERT_H_VIC_CL02	10000 - 12000	Arms Up	Right Hip	0.8634	0	0.0501	0.0026	0.8492	0	50.3058	33.5740
7	ERT_H_VIC_CS03	1000 - 3000	Arms Down	Left Hip	0.7536	0	0.0560	0.0037	0.8579	0	58.1460	58.8517
8	ERT_H_VIC_CS03	5000 - 7000	Arms on Chest	Left Hip	0.8410	0	0.0579	0.0037	0.9007	0	56.7146	46.6504
9	ERT_H_VIC_CS03	9000 - 11000	Arms Up	Left Hip	0.9036	0	0.0619	0.0039	0.9029	0	56.2516	49.7976
10	ERT_H_VIC_CS02	1000 - 3000	Arms Down	Left Hip	0.2870	1.6090e-39	0.0509	0.0065	0.8105	0	72.4245	52.1075
11	ERT_H_VIC_CS02	5000 - 7000	Arms on Chest	Left Hip	0.3081	1.6465e-45	0.0492	0.0071	0.8501	0	68.7540	47.0245
12	ERT_H_VIC_CS02	9000 - 11000	Arms Up	Left Hip	0.2533	6.2254e-31	0.0483	0.0074	0.8289	0	80.5525	50.4850
13	ERT_H_VIC_CO2	2000 - 4000	Arms Down	Right Hip	0.8727	0	0.0768	0.0132	0.7715	0	67.8086	54.3127
14	ERT_H_VIC_CO1	10200 - 12200	Arms Down	Right Hip	1.6535e-04	0.4971	0.0631	0.0153	0.5144	8.6482e-136	79.8439	52.8590
Mean					0.7386		0.0549		0.8326		57.7372	
Standard Error					0.1974		0.0147		0.2225		15.4309	

**Table 13. Statistics results of subject R**

Subject R					Knee Positions				Foot Reaction Forces			
No.	Ref. Hip Marker File Name	From Frame To Frame	Position of Arms	Selected Hip Marker	Correlation		Differences		Correlation		Differences	
					Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )	Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )
1	ERT_R_VIC_CL03	1000 - 3000	Arms Down	Right Hip	0.8938	0	0.0177	0.0095	0.8912	0	69.6965	52.0980
2	ERT_R_VIC_CL03	5000 - 7000	Arms on Chest	Right Hip	0.9365	0	0.0167	0.0083	0.8798	0	70.4334	60.9158
3	ERT_R_VIC_CL03	9000 - 11000	Arms Up	Right Hip	0.9679	0	0.0167	0.0094	0.8978	0	66.4937	50.5476
4	ERT_R_VIC_CL02	1500 - 3500	Arms Down	Right Hip	0.4243	1.7213e-88	0.0182	0.0064	0.8568	0	75.1720	44.9343
5	ERT_R_VIC_CL02	6000 - 8000	Arms on Chest	Right Hip	0.0644	0.0020	0.0205	0.0060	0.8497	0	79.1389	42.6183
6	ERT_R_VIC_CL02	10000 - 12000	Arms Up	Right Hip	0.2187	2.2903e-23	0.0219	0.0066	0.8600	0	73.6084	45.4206
7	ERT_R_VIC_CS03	1000 - 3000	Arms Down	Right Hip	0.8800	0	0.0153	0.0069	0.8666	0	76.3371	61.7973
8	ERT_R_VIC_CS03	6000 - 8000	Arms on Chest	Right Hip	0.8696	0	0.0141	0.0053	0.9003	0	76.6362	54.8719
9	ERT_R_VIC_CS03	10000 - 12000	Arms Up	Right Hip	0.9109	0	0.0152	0.0062	0.9110	0	73.8291	55.7555
10	ERT_R_VIC_CS02	1000 - 3000	Arms Down	Right Hip	0.4088	1.1378e-81	0.0204	0.0067	0.8863	0	85.6024	48.6947
11	ERT_R_VIC_CS02	5000 - 7000	Arms on Chest	Right Hip	0.4679	1.3840e-109	0.0209	0.0071	0.8985	0	81.8215	47.9617
12	ERT_R_VIC_CS02	9000 - 11000	Arms Up	Right Hip	0.4253	6.0786e-89	0.0232	0.0087	0.9063	0	83.1274	50.5188
13	ERT_R_VIC_CO2	7000 - 9000	Arms Down	Right Hip	0.9303	0	0.0239	0.0147	0.7419	0	70.3956	51.1446
14	ERT_R_VIC_CO1	7000 - 9000	Arms Down	Left Hip	0.9567	0	0.0165	0.0140	0.7188	5.6708e-318	67.8538	38.5010
Mean					0.6682		0.0187		0.8618		75.0104	
Standard Error					0.1786		0.0050		0.2303		20.0474	

**Table 14. Statistics results of subject S**

Subject S					Knee Positions				Foot Reaction Forces			
No.	Ref. Hip Marker File Name	From Frame To Frame	Position of Arms	Selected Hip Marker	Correlation		Differences		Correlation		Differences	
					Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )	Corr. Coeff. (r)	P value	Mean (μ)	STD (s <sub>sd</sub> )
1	ERT_S_VIC_CL03	1000 - 3000	Arms Down	Left Hip	0.7527	0	0.0198	0.0112	0.8508	0	67.0626	43.4137
2	ERT_S_VIC_CL03	5000 - 7000	Arms on Chest	Left Hip	0.8038	0	0.0179	0.0082	0.8659	0	62.9544	42.8146
3	ERT_S_VIC_CL03	9000 - 11000	Arms Up	Left Hip	0.7950	0	0.0170	0.0078	0.8773	0	60.7958	39.1795
4	ERT_S_VIC_CL02	1500 - 3500	Arms Down	Left Hip	0.0193	0.1938	0.0180	0.0068	0.8080	0	67.3817	39.8699
5	ERT_S_VIC_CL02	5000 - 7000	Arms on Chest	Left Hip	-0.0315	0.9205	0.0168	0.0061	0.7630	0	63.5001	42.5259
6	ERT_S_VIC_CL02	9000 - 11000	Arms Up	Left Hip	-0.0283	0.8968	0.0169	0.0060	0.8079	0	62.0691	38.2261
7	ERT_S_VIC_CS03	1000 - 3000	Arms Down	Left Hip	0.8746	0	0.0197	0.0085	0.8745	0	62.7147	38.1375
8	ERT_S_VIC_CS03	5000 - 7000	Arms on Chest	Left Hip	0.8105	0	0.0181	0.0075	0.8738	0	61.1321	36.6038
9	ERT_S_VIC_CS03	9000 - 11000	Arms Up	Left Hip	0.8541	0	0.0168	0.0070	0.8663	0	60.3124	38.6471
10	ERT_S_VIC_CS02	1000 - 3000	Arms Down	Left Hip	-0.0142	0.7375	0.0161	0.0070	0.8119	0	60.6608	33.4505
11	ERT_S_VIC_CS02	5000 - 7000	Arms on Chest	Left Hip	-0.0282	0.8958	0.0167	0.0064	0.8402	0	60.9915	30.2677
12	ERT_S_VIC_CS02	9000 - 11000	Arms Up	Left Hip	0.0459	0.0200	0.0167	0.0072	0.8513	0	60.7122	33.5198
13	ERT_S_VIC_CO2	7000 - 9000	Arms Down	Left Hip	0.9174	0	0.0155	0.0108	0.8993	0	60.7147	48.7754
14	ERT_S_VIC_CO1	8000 - 10000	Arms Down	Right Hip	0.63863	8.8330e-279	0.0184	0.0187	0.6851	2.3302e-277	77.4340	39.3293
Mean					0.4578		0.0175		0.8340		63.4597	
Standard Error					0.1224		0.0047		0.2229		16.9603	

**Table 15. Statistics results of the eight subjects**

Subject ID	Knee Positions		Foot Reaction Forces	
	Mean of Corr. Coeff.	Mean of Differences	Mean of Corr. Coeff.	Mean of Differences
A	0.9027	0.0084	0.8461	51.6520
C	0.9457	0.0106	0.8733	26.7305
N	0.6650	0.0242	0.9131	32.3716
P	0.8960	0.0114	0.8649	31.6040
F	0.5402	0.0096	0.8981	29.9116
H	0.7386	0.0549	0.8326	57.7372
R	0.6682	0.0187	0.8618	75.0104
S	0.4578	0.0175	0.8340	63.4597
<b>Mean of the Means</b>	<b>0.7268</b>	<b>0.0194</b>	<b>0.8655</b>	<b>46.0596</b>
<b>Standard Error of the Means</b>	<b>0.2570</b>	<b>0.0069</b>	<b>0.3060</b>	<b>16.2845</b>

As shown on table 6, the eight subjects' heights are ranged from 1.60 m to 1.85 m and their weights are ranged from 57.8 kg to 94.5 kg. According to the statistics results shown on tables 7 – 15, we can see that the calculated knee positions of subject A, C, and P significantly correlate to their knee markers with the differences in values approximately 1 cm. Nonetheless, the correlations between the calculated knee positions and the knee markers of subject N, H, R and S are less. This might be because the knee markers did not appear on the motion capturing system consistently, or the knee markers were placed on the different knee positions from the body measurements. The overall mean of the means of the correlation coefficients of the knee positions of the eight subjects is 0.7268 with the standard error of 0.2570. This shows that between the calculated knee positions and the knee markers are quite related with the mean of the means of the differences of 0.0194 m (1.94 cm).

Moreover, the calculated foot reaction forces of all eight subjects highly correlate to the real force data from force plates with the overall mean of the means of the correlation coefficients of 0.8655 and the standard error of 0.3060. The means of the differences are ranged from 26.7305 N to 75.0104 N, and the mean of the means of the differences is 46.0596 N. The means of the differences in foot reaction forces of subject A, H, R, and S relatively higher than the rest of the subjects.

## 10.4 User Interface Design

Using MATLAB GUIDE, the user interface was designed for the user to set input parameters for each individual subject, plot hip marker data, select time frames of hip data to calculate and simulate the results of squats on the centrifuge and those on the control station. It consists of five panels (subject parameters, centrifuge parameters, select position of arms, weights of equipment, and hip marker data) and two main buttons for the centrifuge simulation plot and the control station simulation plot as shown on figure 46.

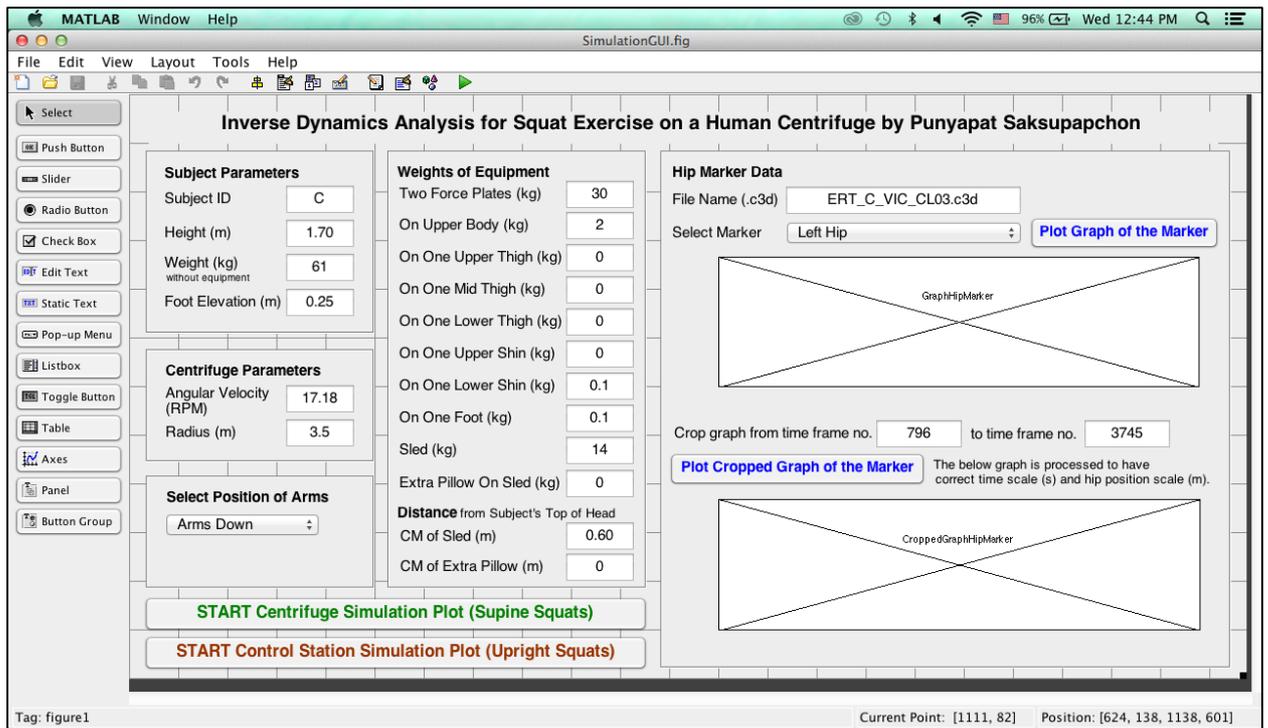


Figure 46. User interface of the simulation

When the user runs the simulation tool, the user interface will be appeared as shown on figure 47. After adjusting the input parameters and the file name of hip marker, the user should select the hip marker, which there are two options: left hip and right hip, and plot the marker graph by clicking the “Plot Graph of the Marker” button. Then, the user can crop an interval of time frames of the hip marker graph to calculate only the interesting part and plot the cropped graph by clicking the “Plot Cropped Graph of the Marker” button. And then, the user should select the position of arms, which there are three options: arms down, arms on chest, and arms up, to match to the selected cropped hip marker frames. Lastly, the user needs to either click on the “START Centrifuge Simulation Plot (Supine Squats)” button to plot the simulation results of the squats on the centrifuge, or click on the “START Control Station Simulation Plot (Upright Squats)” button to plot the simulation results of the squats on the control station.

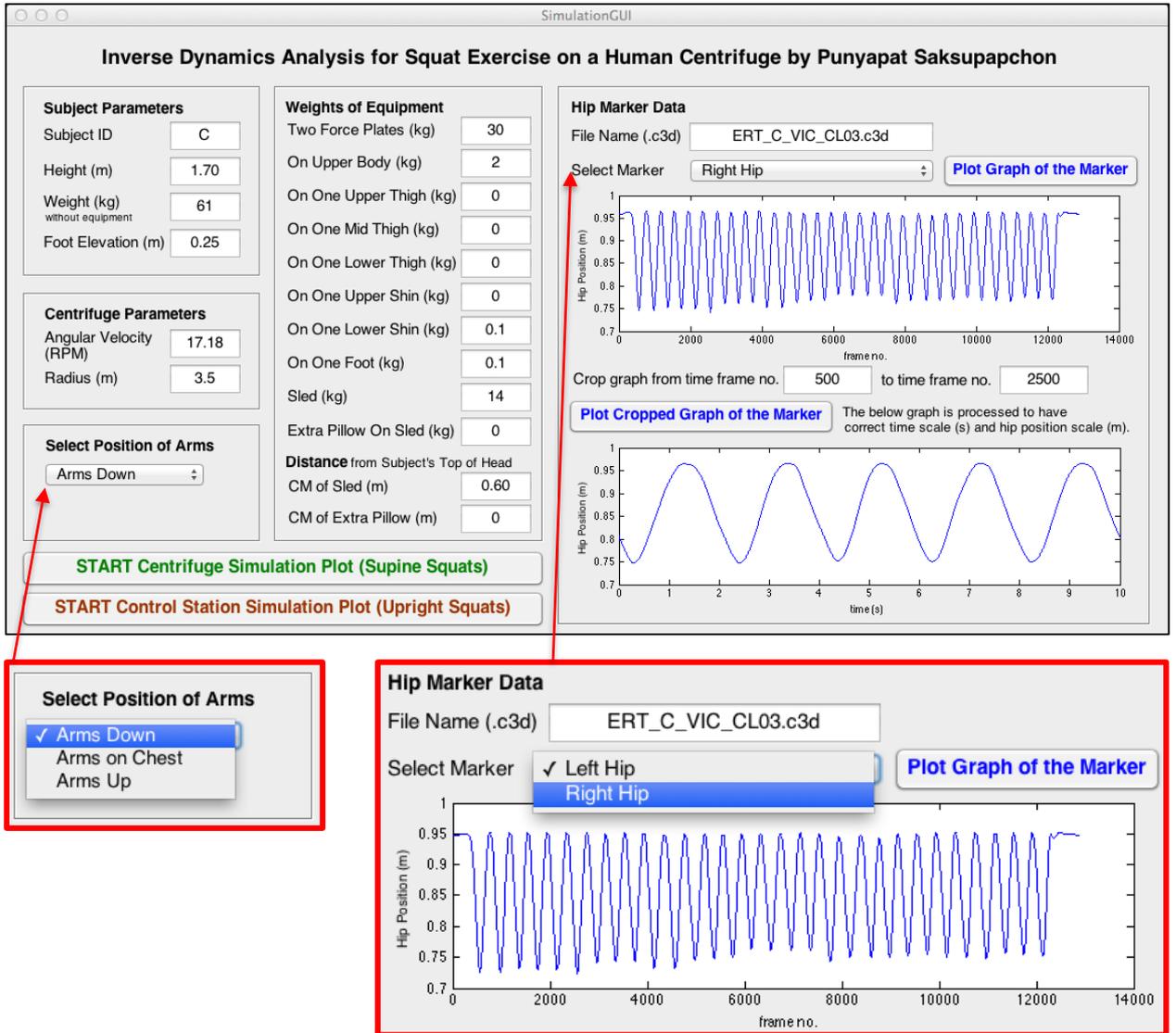


Figure 47. User interface of the simulation with the input parameters

## 10.5 Centrifuge Simulation Plot Window

The title of the simulation plot window shows the file name of the selected hip marker and the numbers of the selected cropped frames. Also, there are 13 tabs to display the results including:

1. All X-Positions
2. Knee Positions – *Comparing to the real data from knee marker*
3. Knee Angles
4. Velocities
5. Coriolis Forces
6. Accelerations
7. Foot Reaction Forces – *Comparing to the real data from force plates*
8. Torques on 1 Knee (by Centrifugal Forces on x axis)
9. Torques on 1 Knee (by Dynamic Squat Forces on x axis)
10. Torques on 1 Ankle (by Centrifugal Forces on x axis)
11. Torques on 1 Ankle (by Dynamic Squat Forces on x axis)
12. Torques on 1 Ankle and 1 Hip (by Coriolis Forces on z axis)
13. Mechanical Work

## An example to show the centrifuge simulation plot results

For this report, the right hip marker of subject C on the centrifuge at radius of 3.5 m was selected to display the results of the simulation tool. The cropped graph was from frame 5000 to 7000, in which the subject was performing squats with arms on chest. The simulation plot results are shown on figures 49 – 61.

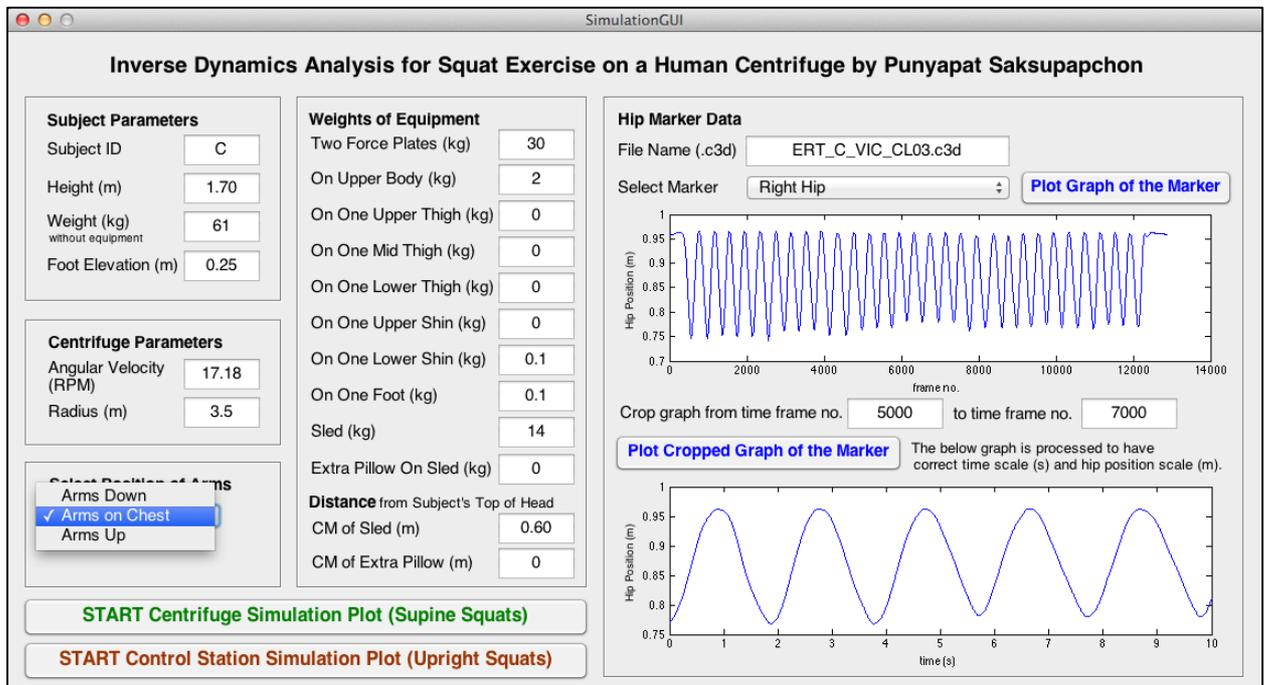


Figure 48. An example for simulation results of subject C on the centrifuge

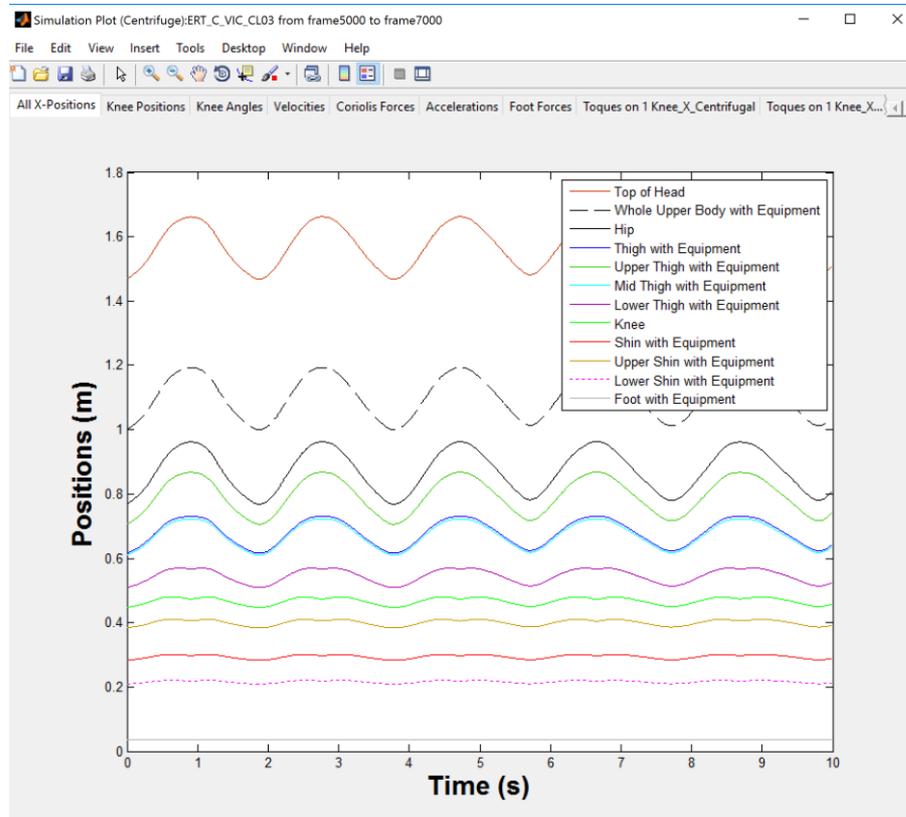


Figure 49. Centrifuge Simulation plot tab 1 – All X Positions

The positions on each body part along x-axis are shown on figure 49. The positions of the center of mass of upper body and the top of head follow the rhythm of the hip position curve. The center of mass of the mid-thigh is slightly lower than the center of mass of the whole thigh.

The comparison of the calculated knee positions to the real data from the knee marker on figure 50 shows that they have the same pattern; however, the calculated knee positions are around 1-2 cm lower than the real data. This might be because the knee marker was placed a bit higher than the knee position that was measured during body measurement section on the day before the centrifuge experiment run. Also, the experiment operator did not use the ruler to measure the knee position again when putting the marker on the knee.

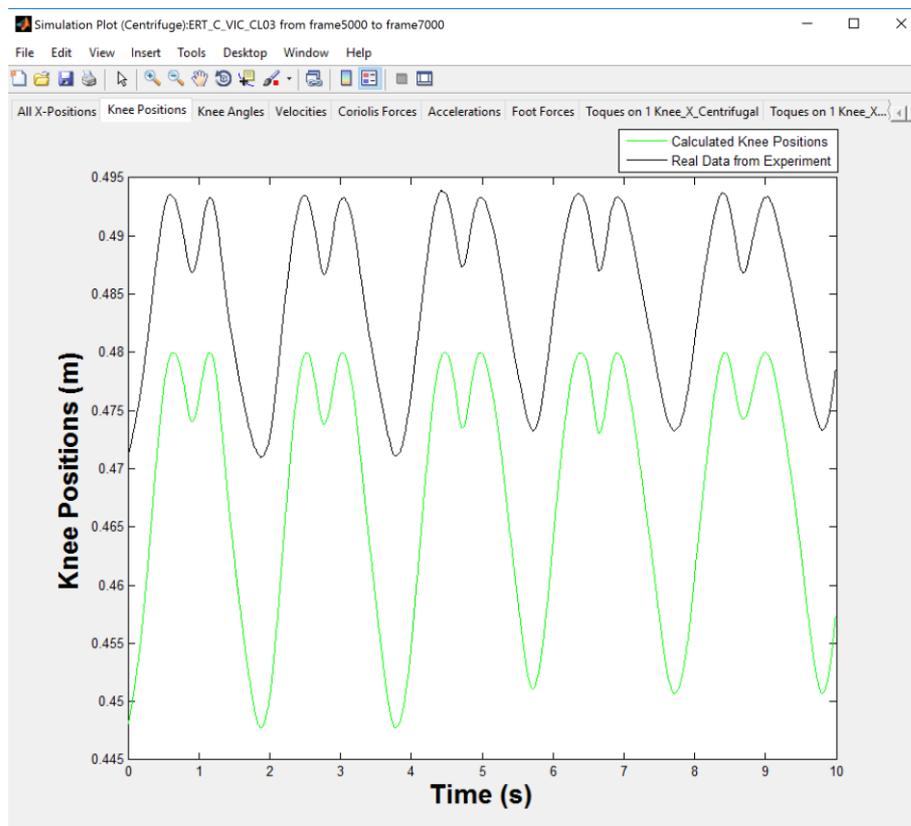


Figure 50. Centrifuge Simulation plot tab 2 – Knee Positions

The knee angles on figure 51 show that the subject did not perform 180° knee extension at up positions and 90° knee flexion at down positions during the squats as expected. Subject C performed squats with approximately 170° knee extension at up positions and 105° knee flexion at down positions.

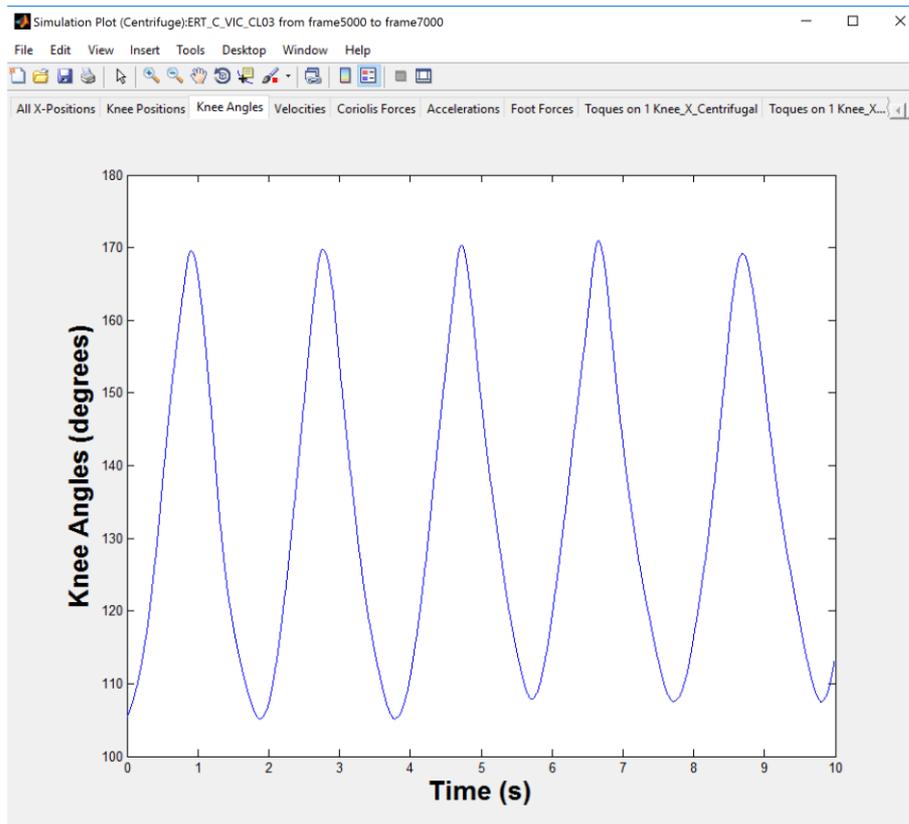


Figure 51. Centrifuge Simulation plot tab 3 – Knee Angles

As shown on figure 52, the velocities of the hip are more than those of the upper thigh, the mid-thigh, the lower thigh, the upper shin and the lower shin respectively. Also, the velocities of the center of mass of the thigh are approximately 7 times higher than those of the center of mass of the shin. The Coriolis forces are dependent to the velocities, so the plot of the velocities of leg segments (figure 52) and the plot of the Coriolis forces acting on each leg segment (figure 53) are in the similar pattern. However, the masses of leg segments are different, so the Coriolis forces acting to the center of mass of the thigh are much (approximately 17 times) more than those acting on the center of mass of the shin because the thigh has more mass and higher velocities than the shin. Moreover, the summation of the Coriolis forces acting on the upper thigh, the mid-thigh and the lower thigh is equal to the Coriolis forces acting on the center of mass of the thigh. Likewise, the summation of the Coriolis forces acting on the upper shin and the lower shin is equal to the Coriolis forces acting on the center of mass of the shin.

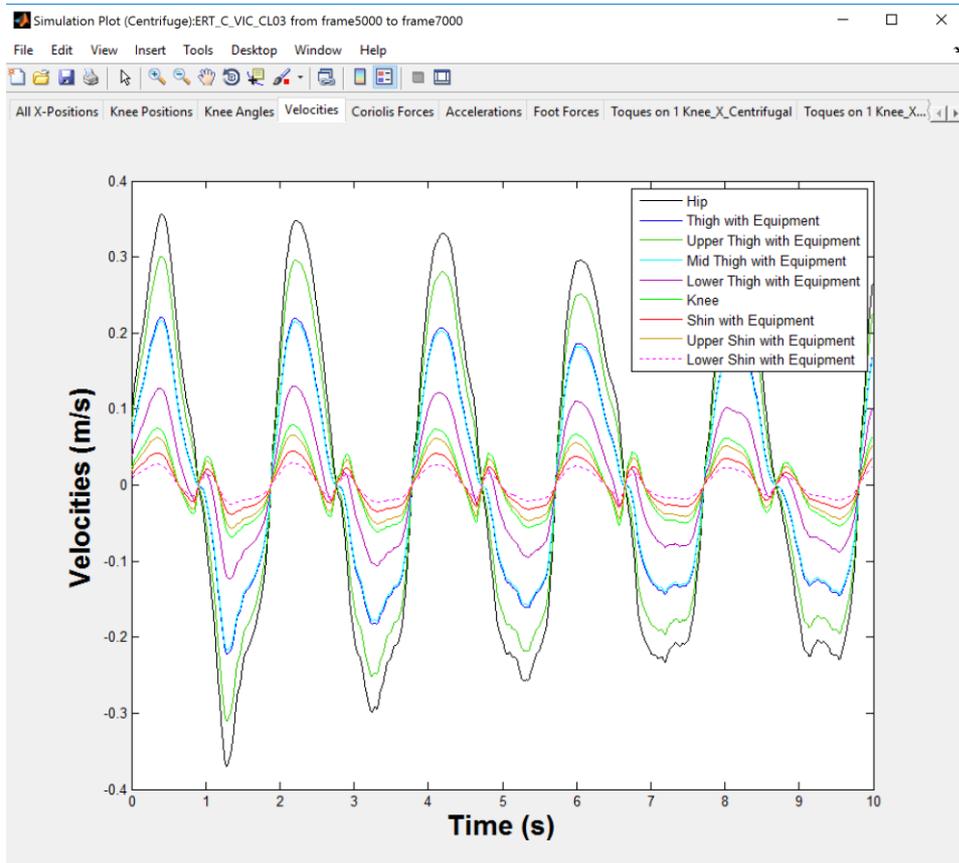


Figure 52. Centrifuge Simulation plot tab 4 – Velocities

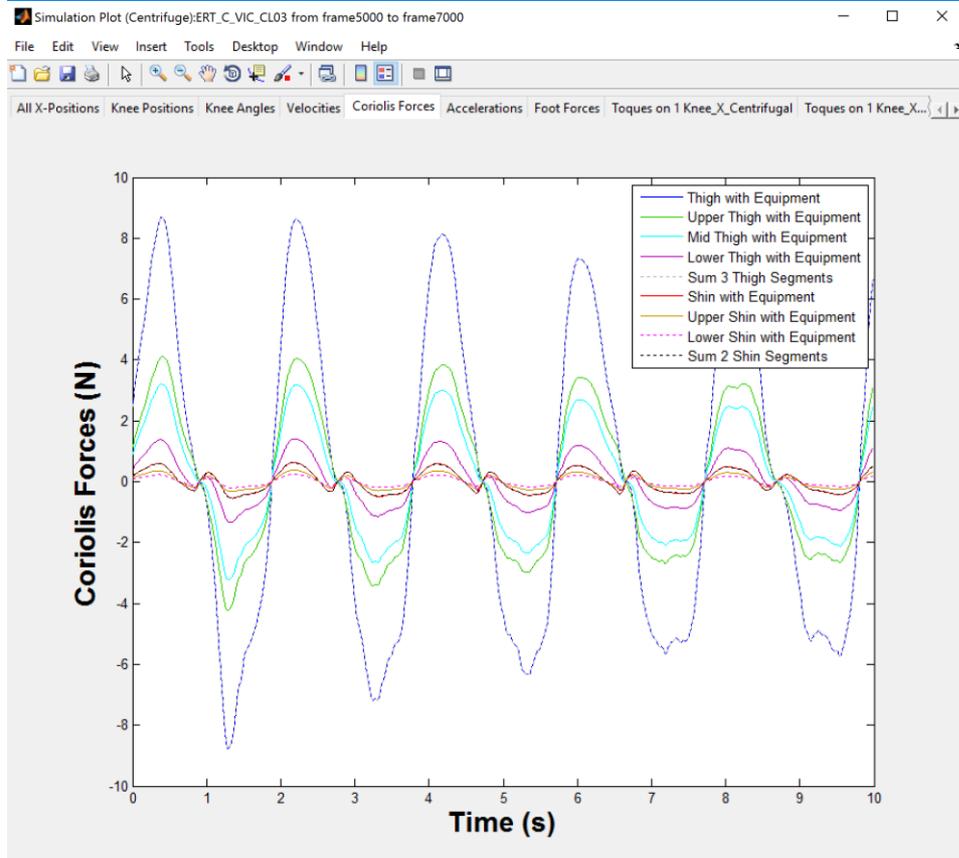


Figure 53. Centrifuge Simulation plot tab 5 – Coriolis Forces

As shown on figure 54, the accelerations of the hip are more than those of the upper thigh, the mid-thigh, the lower thigh, the knee, the upper shin and the lower shin respectively. The accelerations are at the maximal points when the subject was at the down position of the squats.

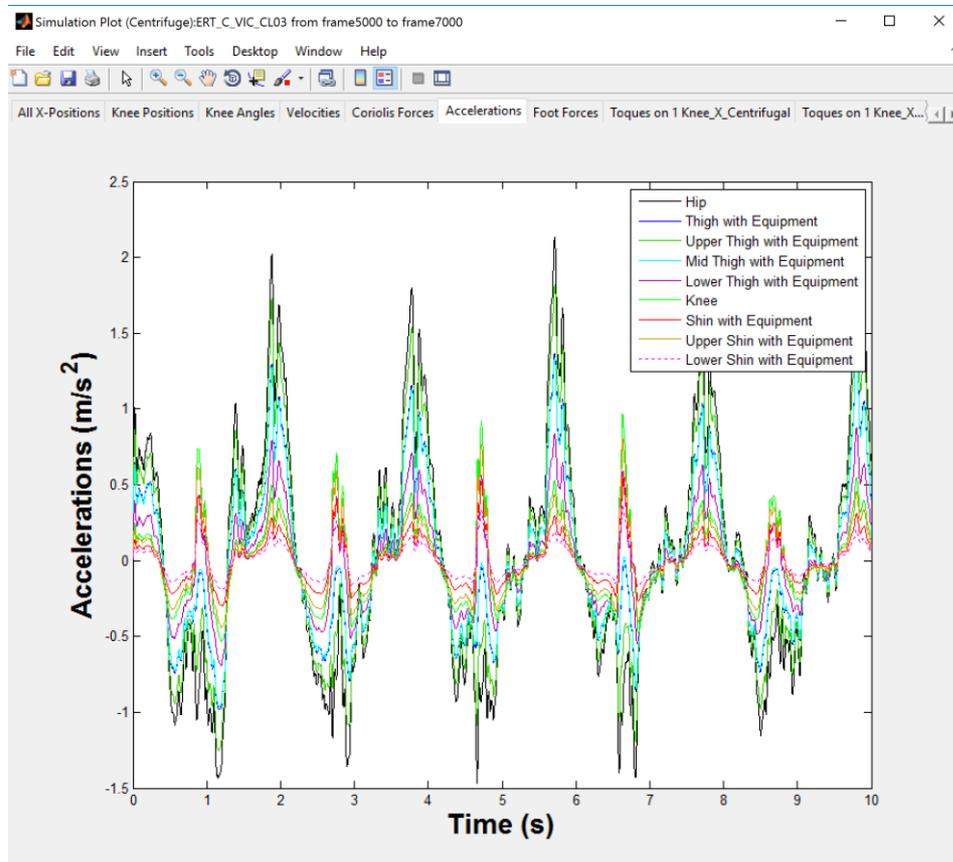


Figure 54. Centrifuge Simulation plot tab 6 – Accelerations

Similarly, the foot reaction forces (shown on figure 55) are at the maximal points when the subject was at the down position of the squats, and at the minimal points when the subject was at the up position of the squats. Besides, the calculated forces have the similar pattern as the real force data graph, but slightly lower in magnitude.

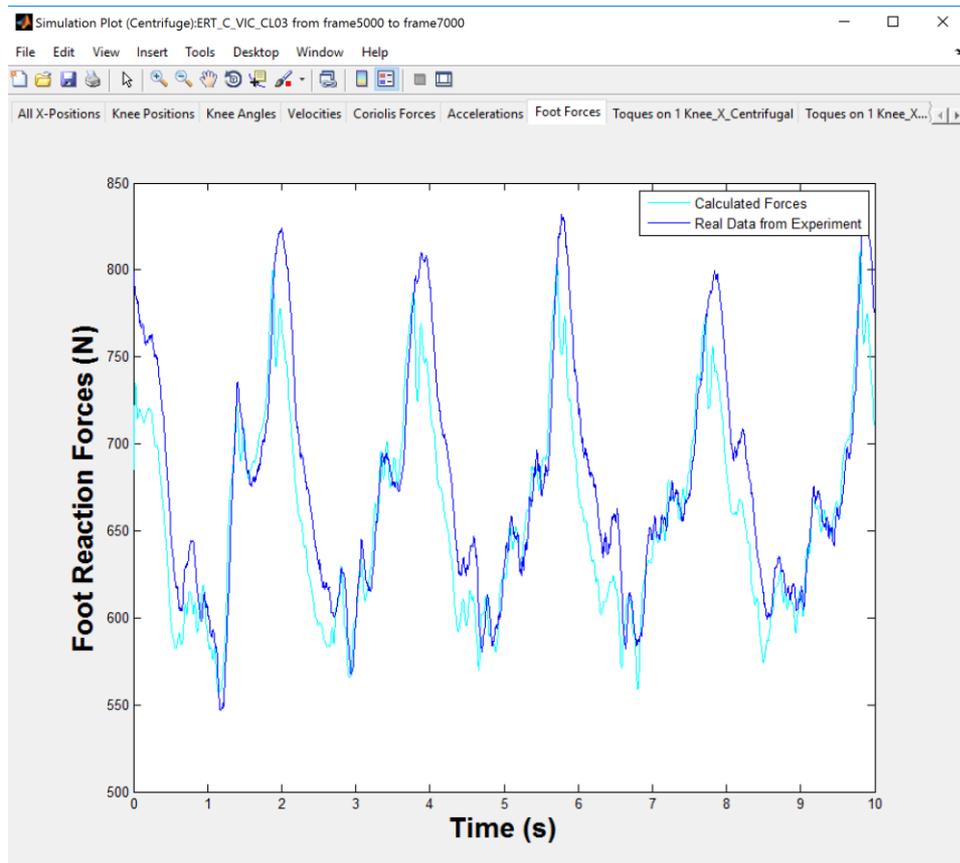


Figure 55. Centrifuge Simulation plot tab 7 – Foot Reaction Forces

According to the torques on a knee joint caused by forces on x-axis shown on figure 56 and figure 57, the magnitudes of torques due to the centrifugal forces are much higher than those of the torques due to the forces from dynamic squats. The main torques come from the mass of the upper body including the masses of the equipment and the sled. Moreover, the combined torques calculated from the three thigh segments are slightly different from the torques calculated from the center of mass of the thigh. Likewise, the combined torques calculated from the two shin segments are slightly different from the torques calculated from the center of mass of the shin. In addition, the torques calculated from the shin are much lower than those from the thigh.

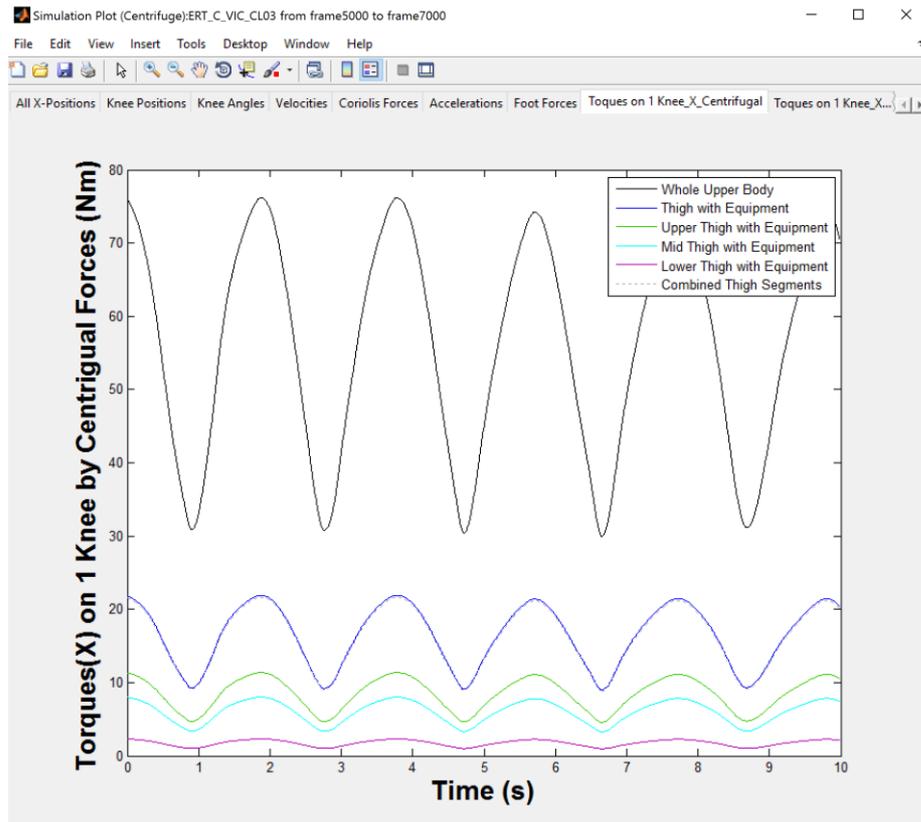


Figure 56. Centrifuge Simulation plot tab 8 – Torques on 1 Knee (by Centrifugal Forces on x axis)

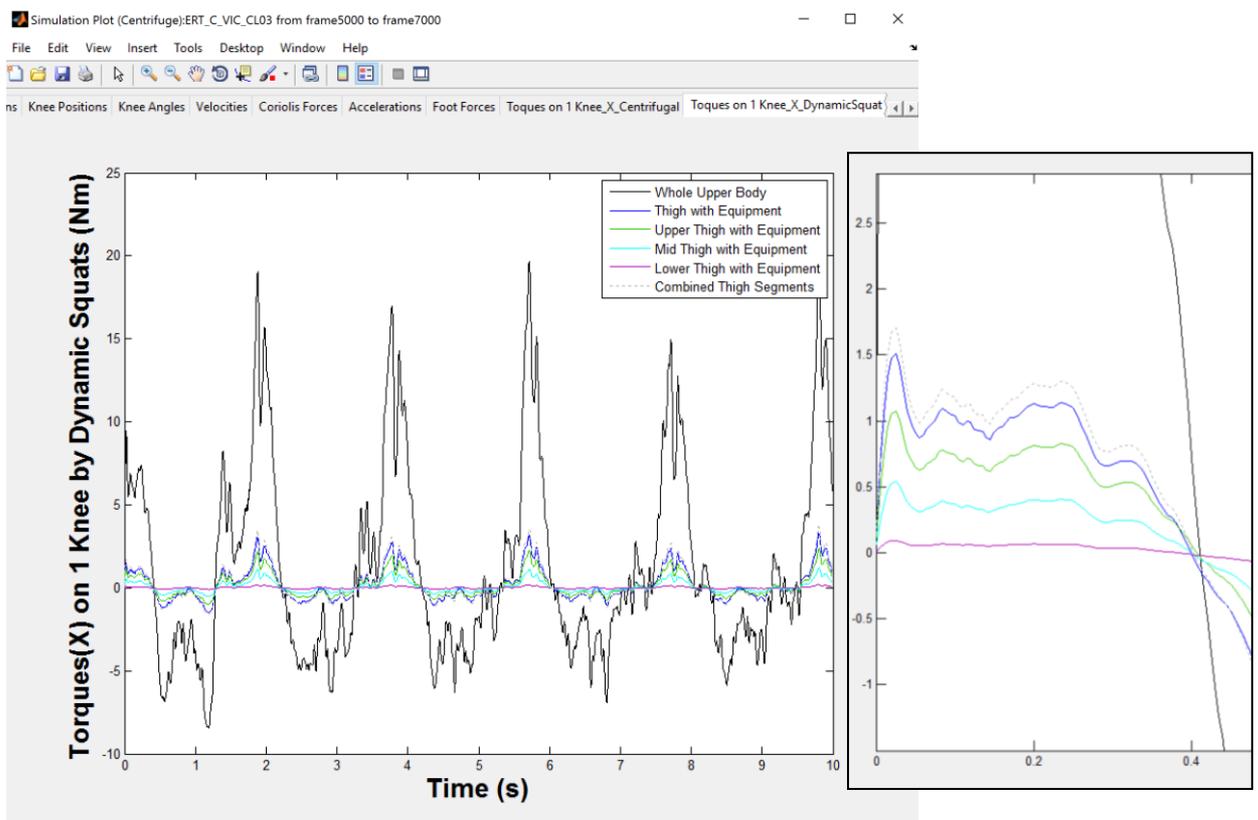


Figure 57. Centrifuge Simulation plot tab 9 – Torques on 1 Knee (by Dynamic Squat Forces on x axis)

According to the torques on an ankle joint shown on figures 58 and 59, the magnitudes of torques due to the centrifugal forces are much higher than those of the torques due to the forces from dynamic squats. As seen on figure 60, the torques on the ankle joint and the hip joint caused by the Coriolis forces acting on the thigh and the shin on z-axis are relatively very small comparing to the torques caused by the forces on x-axis. Moreover, the combined torques calculated from the three thigh segments are slightly different from the torques calculated from the center of mass of the thigh. Likewise, the combined torques calculated from the two shin segments are slightly different from the torques calculated from the center of mass of the shin.

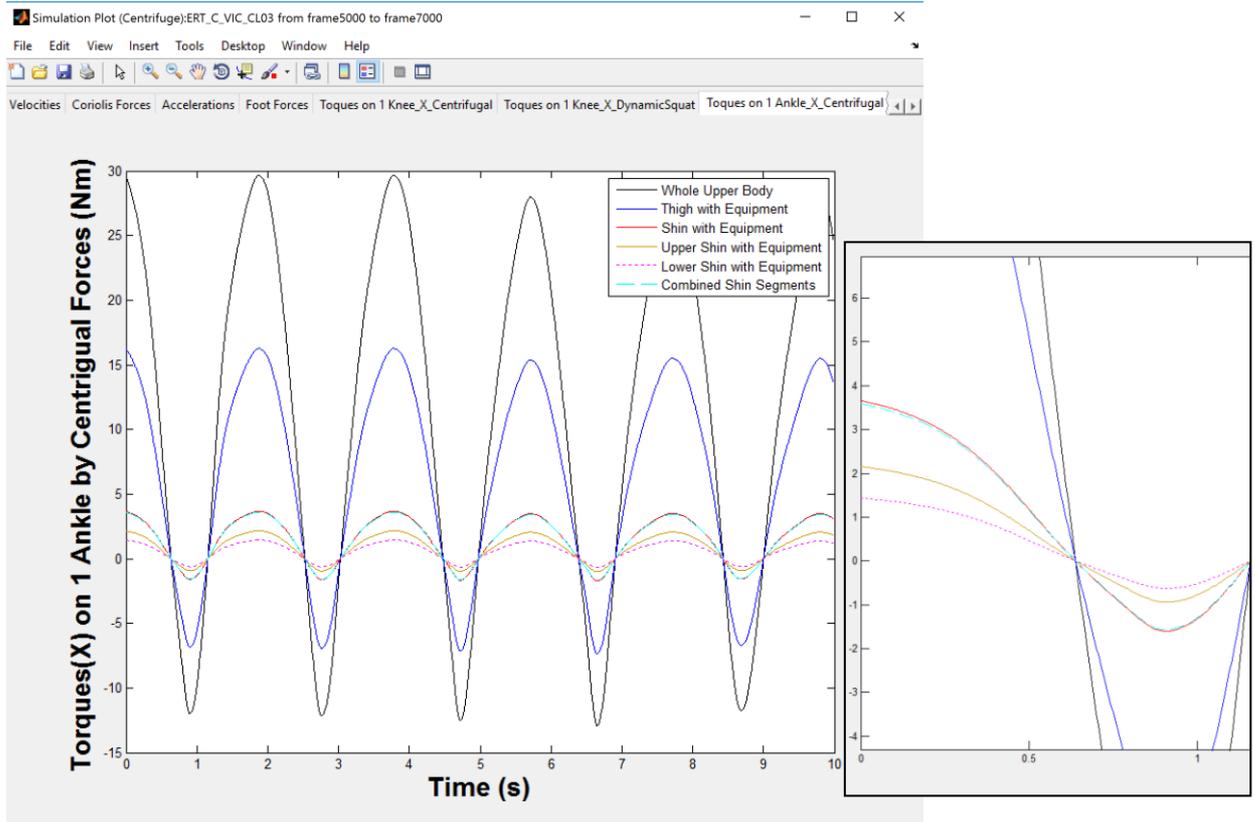


Figure 58. Centrifuge Simulation plot tab 10 – Torques on 1 Ankle (by Centrifugal Forces on x axis)

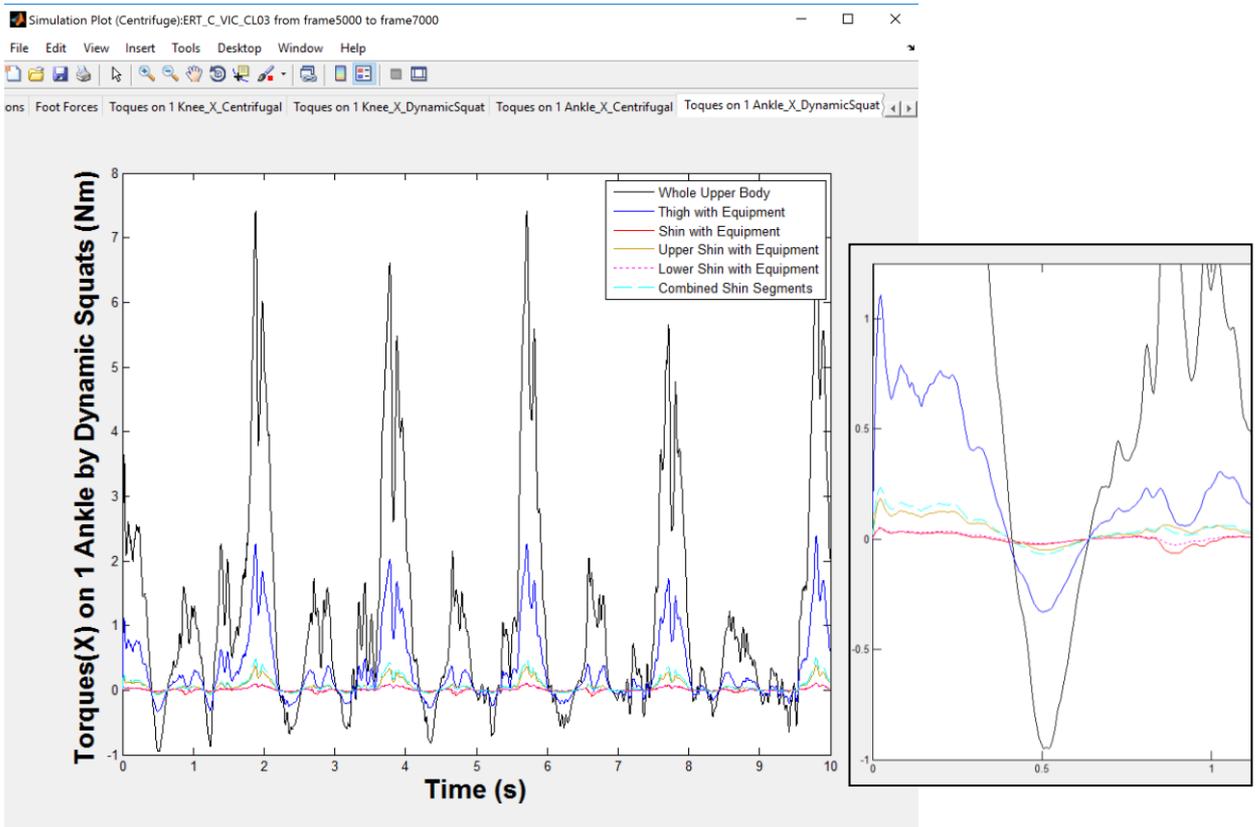


Figure 59. Centrifuge Simulation plot tab 11 – Torques on 1 Ankle (by Dynamic Squat Forces on x axis)

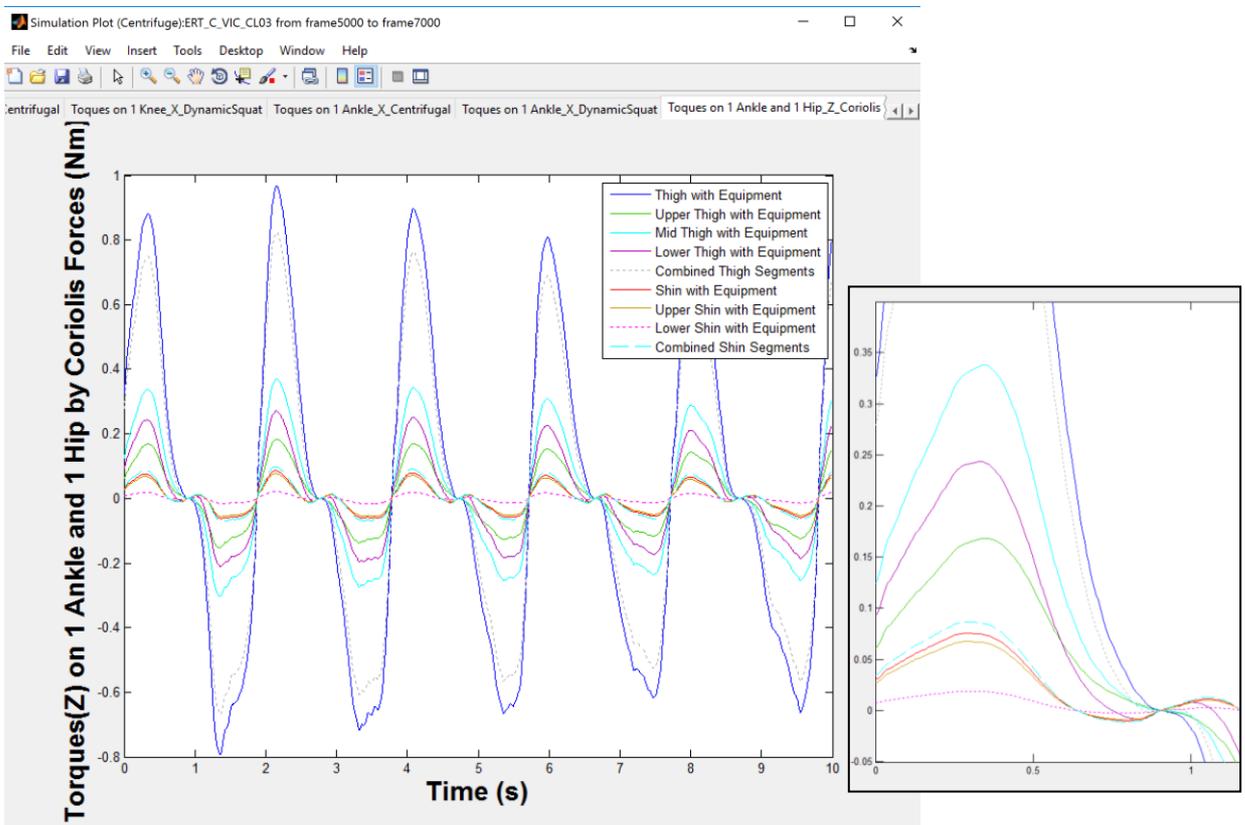


Figure 60. Centrifuge Simulation plot tab 12 – Torques on 1 Ankle and 1 Hip (by Coriolis Forces on z axis)

As shown on figure 68, the mechanical work of Subject C performing squats on the centrifuge at radius of 3.5 meters during these 10 seconds is approximately 930 joules or 220 calories (= 0.22 kilocalories = 0.22 Calories).

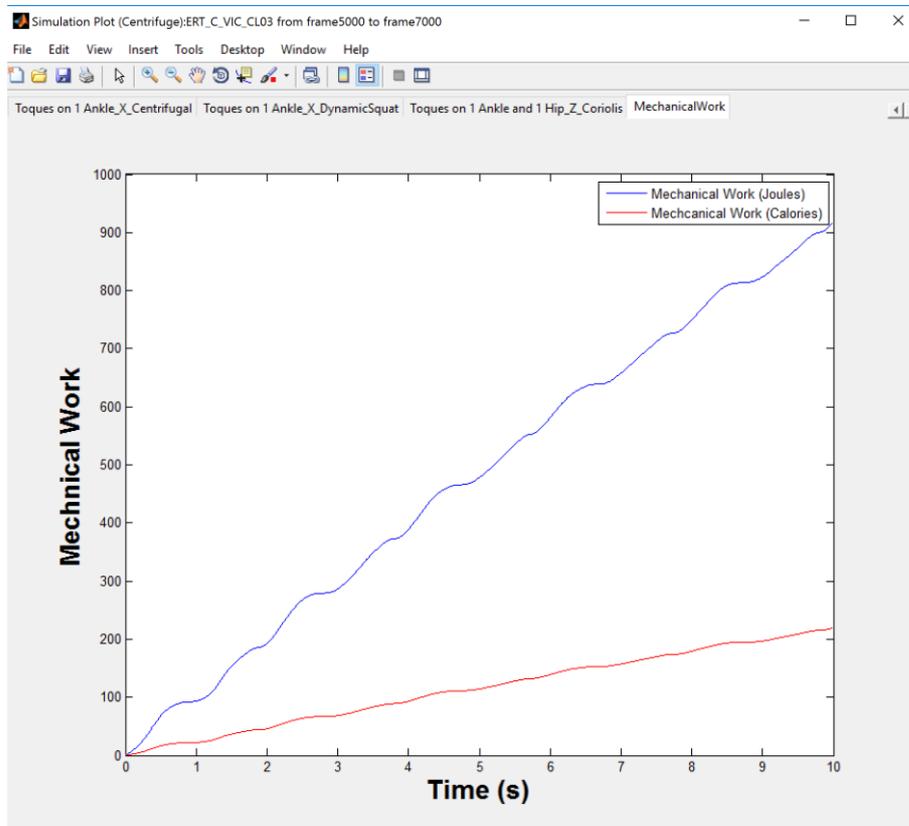


Figure 61. Centrifuge Simulation plot tab 13 – Mechanical Work

## 10.6 Control Station Simulation Plot Window

The title of the simulation plot window shows the file name of the selected hip marker and the numbers of the selected cropped frames. Also, there are 9 tabs to display the results including:

1. All Positions
2. Knee Positions – *Comparing to the real data from knee marker*
3. Knee Angles
4. Velocities
5. Accelerations
6. Foot Reaction Forces – *Comparing to the real data from force plates*
7. Torques on 1 Knee
8. Torques on 1 Ankle
9. Mechanical Work

### An example to show the control station simulation plot results

For this report, the left hip marker of subject C on the control station was selected to display the results of the simulation tool. The cropped graph was from frame 8000 to frame 10000. Although on the control station the subject was performing squats with arms down, without the gravity gradient, this did not affect to the results of the foot reaction forces. The simulation plot results are shown on figures 70.

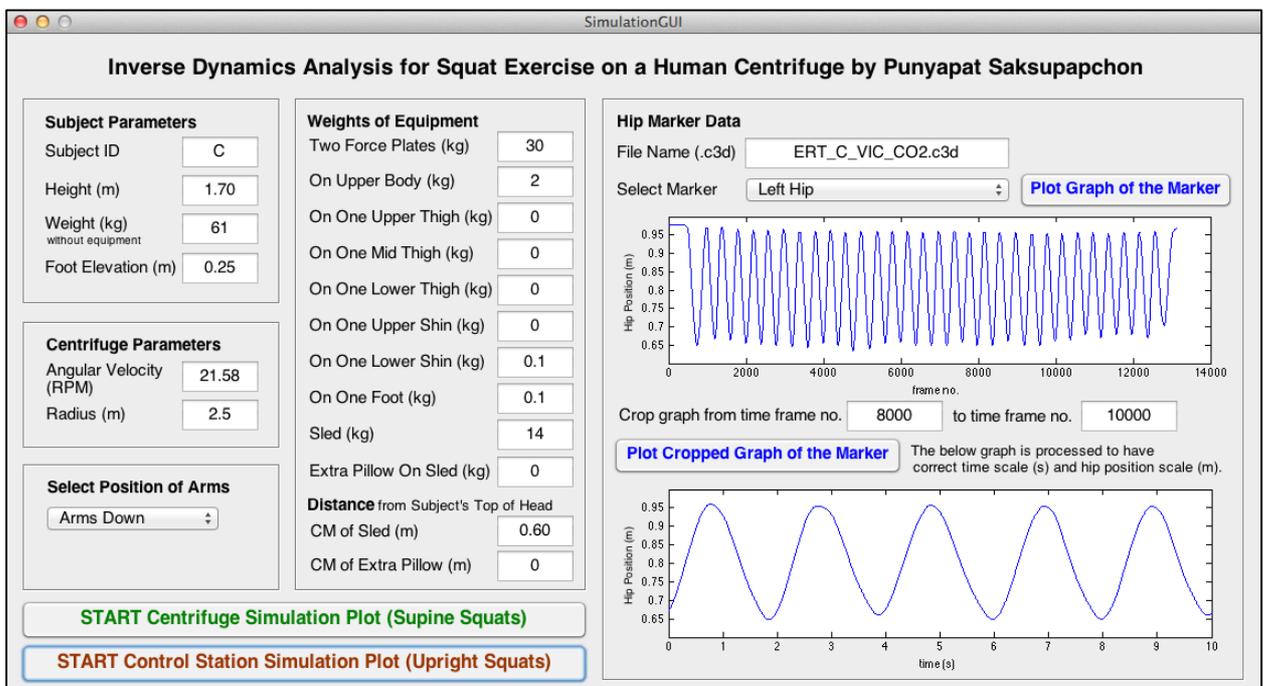


Figure 62. An example for simulation results of subject C on the control station

Since there was no gravity gradient on the control station, the subject's thigh and shin were not segmented into smaller parts for the calculations.

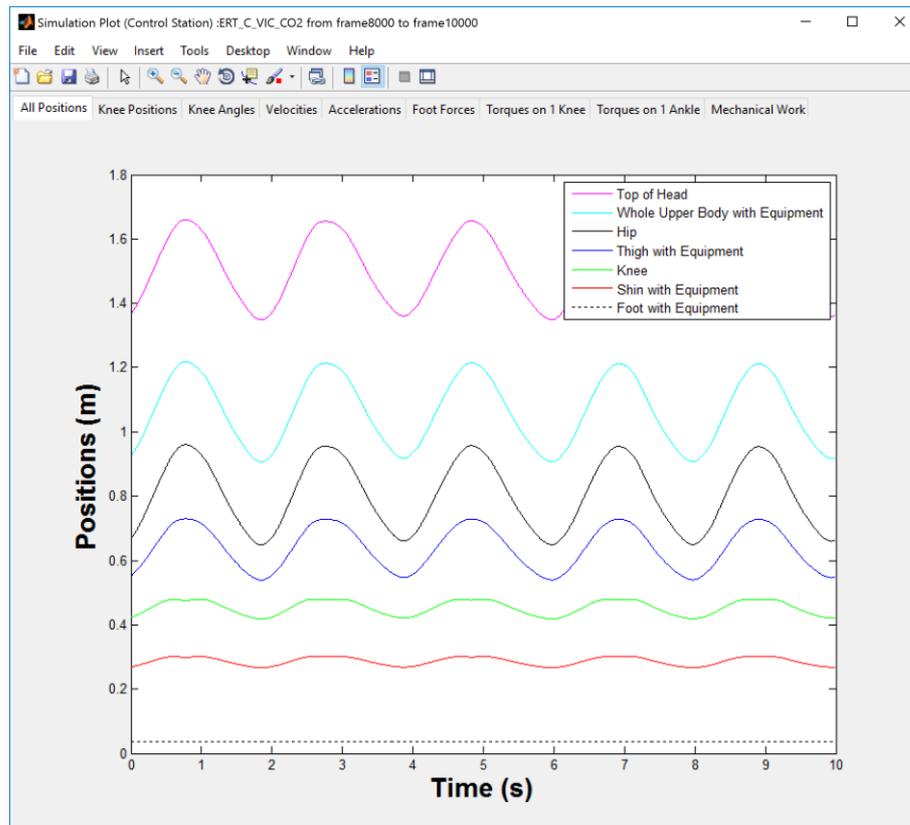


Figure 63. Control Station Simulation plot tab 1 – All Positions

The noticeable different results of the control station comparing to the centrifuge are that Subject C performed squats with approximately  $165^\circ$  knee extension at up positions and  $85^\circ$  knee flexion at down positions (as seen on figure 65), which the body position was deeper and closer to the force plates. The ranges of the body positions during the squat motions are more than those on the centrifuge. Thus, the body parts moved with higher velocities. This generates more mechanical work, as shown on figure 71, the mechanical work of subject C performing squats on the control station during these 10 seconds is approximately 1380 joules or 330 calories (= 0.33 kilocalories = 0.33 Calories).

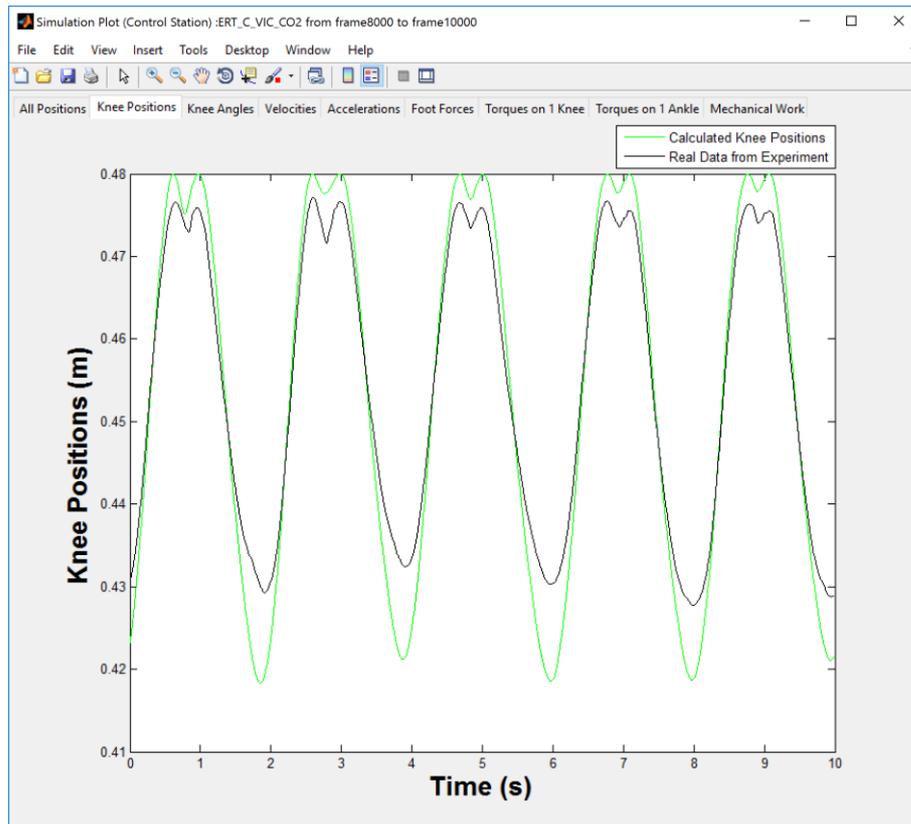


Figure 64. Control Station Simulation plot tab 2 – Knee Positions

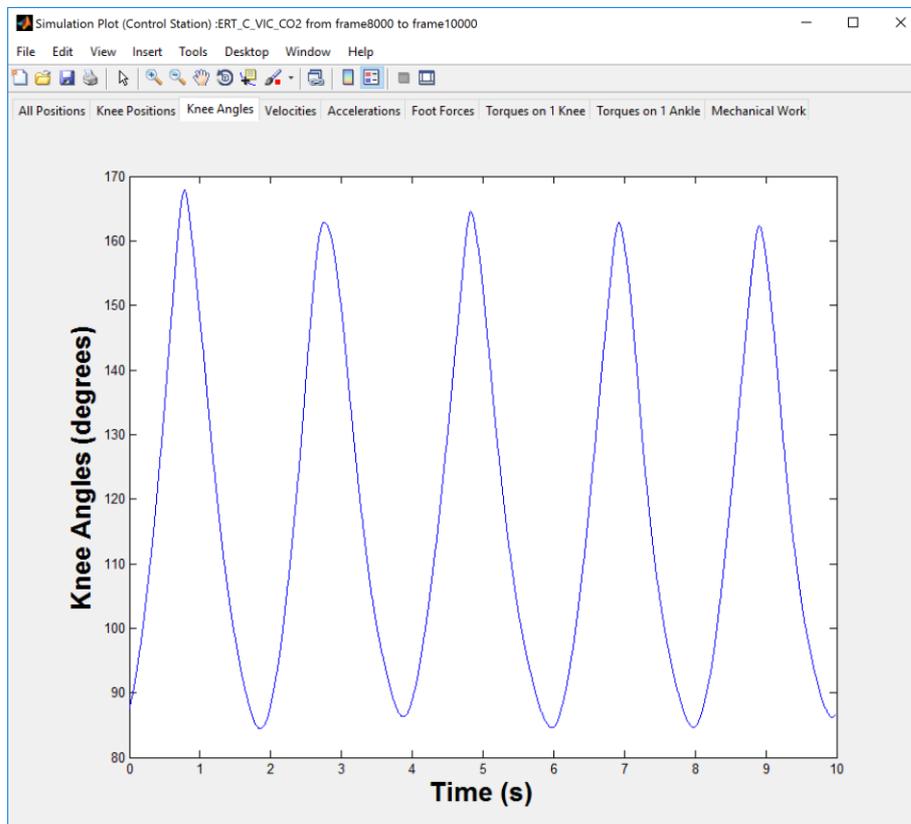


Figure 65. Control Station Simulation plot tab 3 – Knee Angles

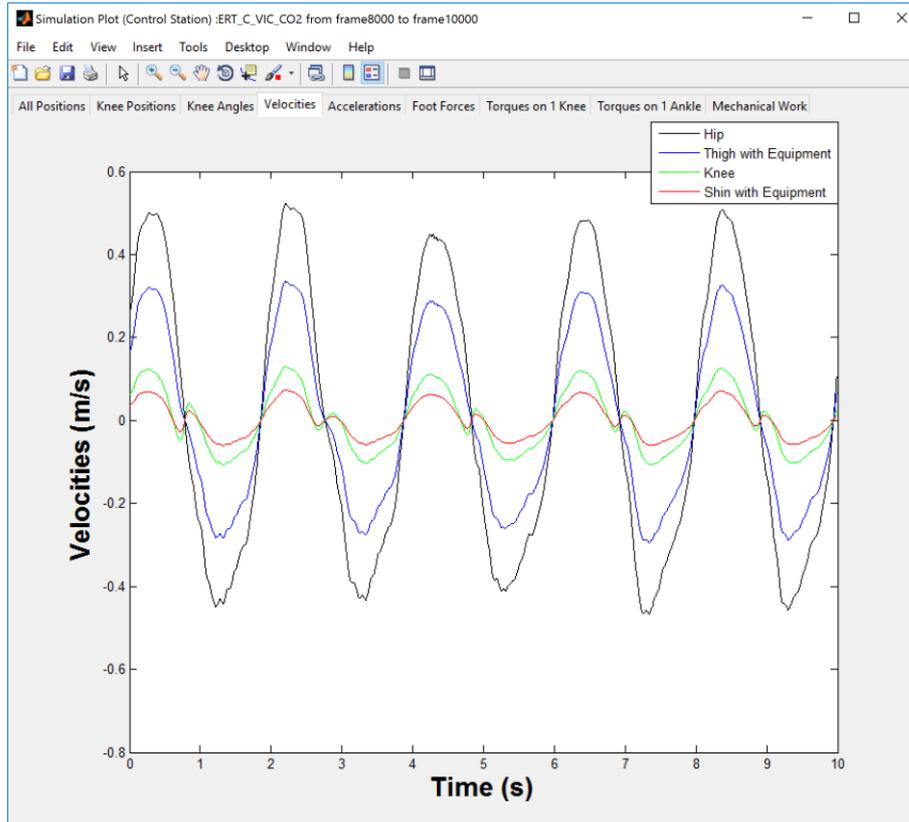


Figure 66. Control Station Simulation plot tab 4 – Velocities

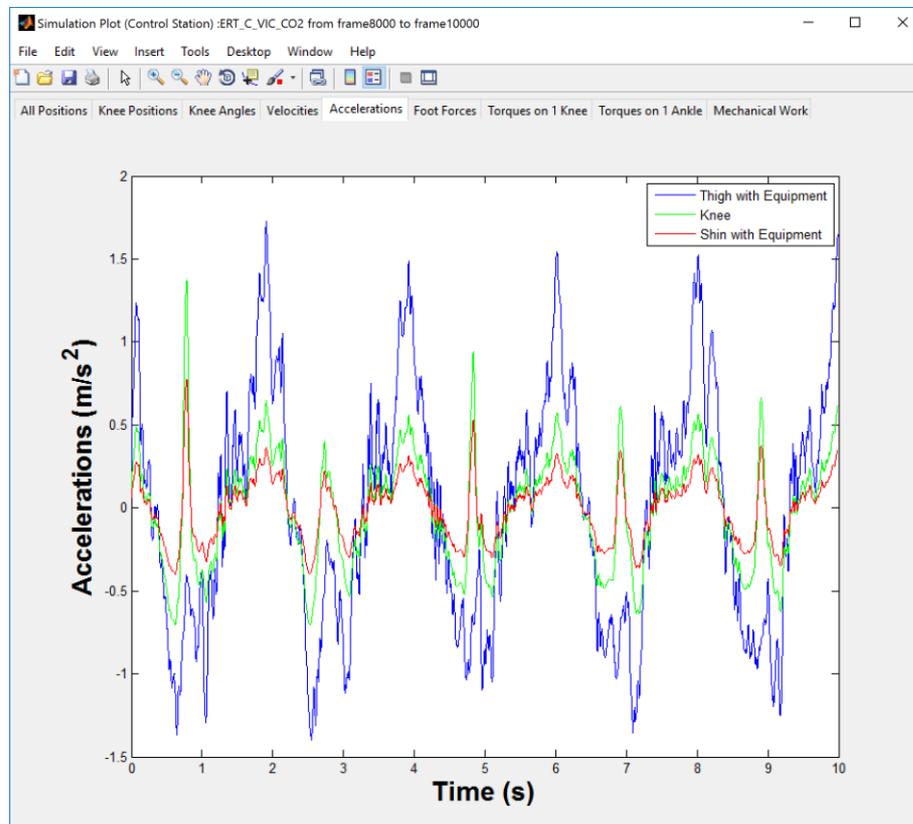


Figure 67. Control Station Simulation plot tab 5 – Accelerations

The magnitudes of peak forces on force plates of the control station are a bit less than those on the centrifuge. This might be caused by the a-bit-higher-than-expected angular velocity of the centrifuge. Besides, the torques on knee, ankle and hip joints of the subject on the control station were caused by forces only on the vertical direction. However, the magnitudes of the torques are comparable to the torques on the joints caused by forces on x-axis of the subject on the centrifuge.

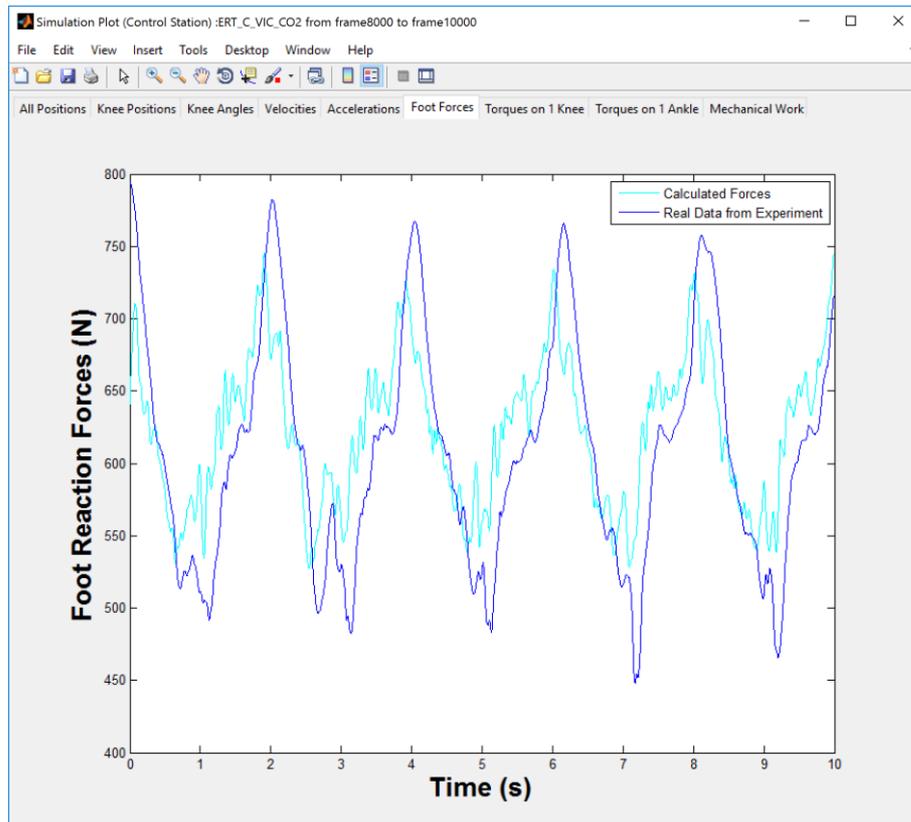


Figure 68. Control Station Simulation plot tab 6 – Foot Reaction Forces

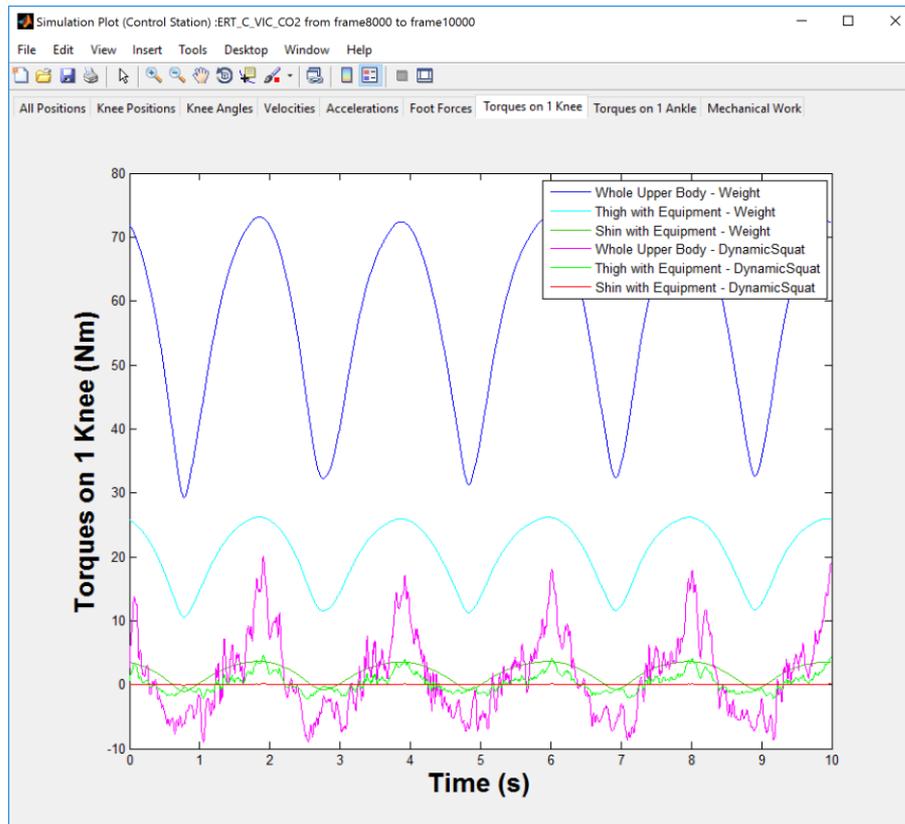


Figure 69. Control Station Simulation plot tab 7 – Torques on 1 Knee

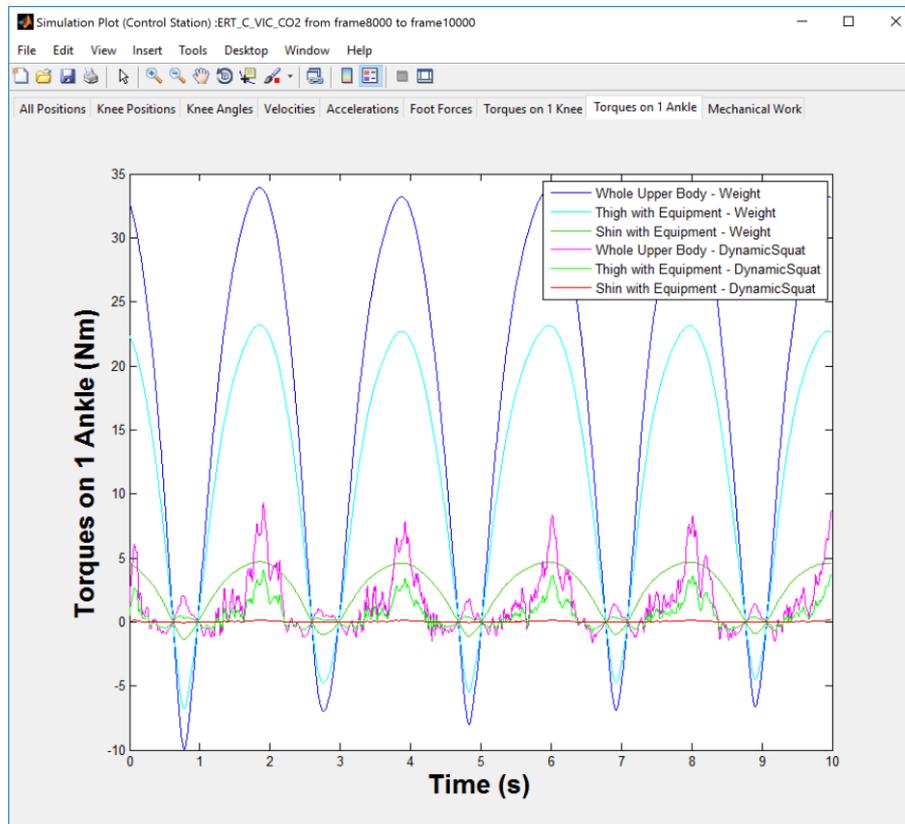


Figure 70. Control Station Simulation plot tab 8 – Torques on 1 Ankle

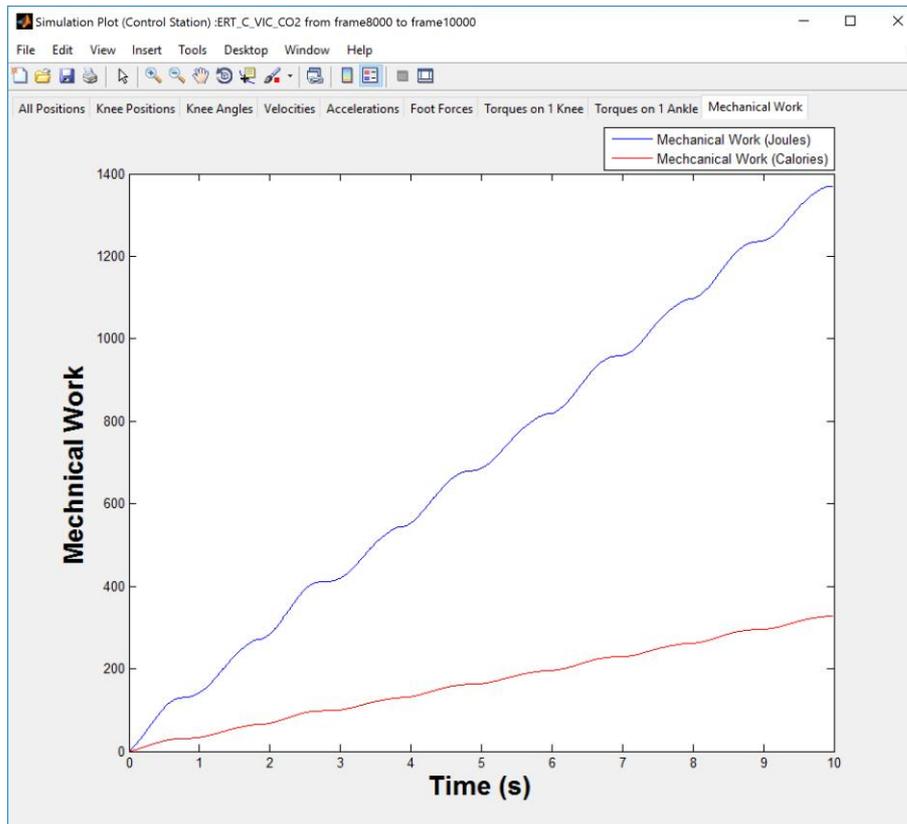


Figure 71. Control Station Simulation plot tab 9 – Mechanical Work

## Chapter 11. Discussions

The results shown on the simulation tool are composed of two main parts: 1) the plotted data for validating the computing models, and 2) the other plots for more information and better analysis. The two plots for validating the computing models are the plots of the knee positions and the foot reaction forces. The results show that the calculated knee positions correlate to the real data of positions of the knee marker with some deviations due to the unsteady visibility of the knee marker on the motion capturing system and the inaccurate placement of the marker on the knee referring to the body measurements. Moreover, the results of the foot reaction forces show that the calculated forces significantly correlate to the real force data from force plates; however, there are some deviations - the magnitudes at the peaks of the calculated forces are less than those of the real data. This might be relevant to the detection of additional fluid shifts from the upper body to the feet of the subject during centrifugation due to the centrifugal accelerations, which should be clarified by the physiological study.

In addition, there should be a set gap between the sled on the centrifuge and the end of the sled track to eliminate the errors of foot reaction forces caused by the sled hitting the end of the sled track. Also, the subjects should be informed that they should not move the body too low and should not make the sled hit the end of the track. This problem may also be improved by using a sensor or a detector that informs the experiment operator on which time frames the sled hits the end of the track. The noises on the signals of the force plates on the centrifuge should also be reduced in order to improve the quality of the force data.

Furthermore, the manual method of body measurements and the process of placing the motion capturing markers on each subject might have some human errors, which affected to the results of the simulations. These processes might be improved by using equipment such as a body scanner to measure the body parts of the subjects, and for the marker placement the positions of the joints should be measured and checked again whether the markers are on the correct positions as same as the data of the body measurements. Moreover, sometimes the hip markers were disappeared (hidden under the subjects' clothes) during squatting down. Hence, the subjects should perform some squatting trials for checking the visibility of the markers especially the hip markers thoroughly before the experiment started.

Moreover, the combined torques calculated from the three thigh segments are slightly different from the torques calculated from the center of mass of the thigh. Likewise, the combined torques calculated from the two shin segments are slightly different from the torques calculated from the center of mass of the shin. Thus, we may use the center of mass of the thigh and the center of mass of the shin for the torques calculations for the further studies.

Besides, during the centrifuge experiment, all subjects performed well and completed the squat exercises without any motion sickness. During the first few squats on the rotating centrifuge, the subjects felt the Coriolis forces deviating their legs. However, after multiple squats, the limb movement were completely natural and indistinguishable from the normal non-rotating environment. Thus, this artificial gravity squat exercise protocol is practicable in reality.

## Chapter 12. Conclusions

In this study, the biomechanical model and simulation for the artificial gravity (supine) squat exercise was developed on MATLAB and validated by the human experiments on the next generation DLR Short-Arm Human Centrifuge (envifuge). The inverse dynamics method was used by obtaining joint orientations, displacements, velocities and accelerations from the inverse kinematics method given body part's positions and mass measurements as the inputs to calculate the joint torques and forces and show the results. In addition, the simulation tool has a user interface that the users can adjust the input parameters such as radius of the centrifuge, rotation rate, and the subject's height, weight, and lengths of body parts. The simulation also demonstrates foot reaction forces, torques, and body movements due to the Coriolis effect and g-gradient.

The ExRoTe study consists of the study of biomechanical part (external motions of the body) and the study of physiological part (internal mechanisms of the body). Since this report focuses only on analyzing the data of biomechanical part mainly from the motion capturing system and the force plates and developing the model and simulation based on these data, the calculated foot reaction forces are deviated from the real force data, which might be caused by the internal mechanisms of the body (fluid shifts and muscle activities). In order to improve the model and simulation, the results from the study of physiological part should be further included. Then the further extensions of the model can be developed such as including the modelling for fluid shifts.

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## **Appendices**

# Appendix A: ExRoTe Motion Capturing Experiment Protocol



Date:

Subject:

Notes:

Positions	Names
Centrifuge Operator	Guido
Medical Doctor	Jörn
Vicon System Operator	Timothy
Experiment Operator and Time Keeper	Punyapat
Subject	X

Part	Activity	Time	Duration	Subject	Vicon System	Centrifuge	Motivation Tool / Profile Signal	File Name		
Part 1	Subject's Body Measurements (40 min)		2 min	Measure Subject's Height & Weight						
			20 min	Measure Body Parts and Foot Elevation						
			8 min	Calculate RPM of centrifuge						
			10 min	Brief squat motions to the subject						
Part 2	Preparation (30 min)	0:00	1 min	Weigh the test subject without equipment	Start Vicon PC	System check				
			5 min	Final Medical Exam	Turn on Vicon Box		Set computer & Tie it on centrifuge			
			1 min	Medical Monitoring Hardware: ECG & Finapress	Check Cameras Setup and Calibration	Measure & Mark feet position on force plate				
			2 min	Harness						
			2 min	12 Markers on Joints	Turn on FP Box					
			2 min	3 Accelerometers on Calfs and Waist + power on	Start Vicon Nexus					
			1 min	Weigh the test subject with equipment	Check Session (F2)					
			1 min	Take photos for references	DV Cam Signal Check					
		0:15	2 min	<b>Subject Enters Centrifuge</b>						
			5 min	Push sledge down, Push subject's shoulders up, Tie harness to the sledge, and Measure voltages at Up and Down positions	Check Markers and Reflections (full range of motion) + Ask subject to move arms down, on chest, & up		Set voltage, Run & Check the motivation tool			
			5 min	Hardware Mangement + Tie legs	Zero Level FPBox					
			2 min	Take photos for references	FP Signal Check		Open "Acknowledge" and Create new file	ERT_X_VIC_CL		
			1 min	Medical Condition check			Start recording sled signal			
		Part 2	Long radius 3.5 m (15 min)	0:30	1 min			Start the centrifuge		
					1 min	Medical Condition check				
	10 s			Stay at Midpoint position (arms downward)	Check force plates	Adjust RPM & Announce 1 g				
0:33				<b>Stay at UP position</b>	<b>Start Trial 1 (MoCap)</b>			ERT_X_VIC_CL01		
	5 s			Place both arms down for 5 s.						
	5 s			Place both arms on chest for 5 s.						
	5 s			Place both arms up for 5 s.						
				<b>Stay at DOWN position (90deg flexion)</b>						
	5 s			Place both arms down for 5 s.						
	5 s			Place both arms on chest for 5 s.						
	5 s			Place both arms up for 5 s.						
0:34	30 s			Rest	<b>Stop Trial 1</b>					
	1 min			Medical Condition check	Check the trial file					
					Create New Trial with MoCap					
0:36					<b>Start Trial 2 (MoCap)</b>		Select Profile Signal2	ERT_X_VIC_CL02		
	1 min				<b>Start 1min Profile Signal2 (The signal with 2s pause)</b>					
	20 s	With arms down, Squat for 5 rep.								
	20 s	With arms on chest, Squat for 5 rep.								
	20 s	With arms up, Squat for 5 rep.								
0:38	30 s	Rest	<b>Stop Trial 2</b>		<b>Stop 1min Profile Signal2</b>					
	1 min	Medical Condition check	Check the trial file							
			Create New Trial with MoCap							
0:40			<b>Start Trial 3 (MoCap)</b>		Select Profile Signal3	ERT_X_VIC_CL03				
	1 min				<b>Start 1min Profile Signal3 (Continuous signal)</b>					

Part	Activity	Time	Duration	Subject	Vicon System	Centrifuge	Motivation Tool / Profile Signal	File Name
Part 2			20 s	With arms down, Squat for 10 rep.				
			20 s	With arms on chest, Squat for 10 rep.				
			20 s	With arms up, Squat for 10 rep.				
		0:42	30 s	Rest	Stop Trial 3		Stop 1min Profile Signal3	
			1 min	Medical Condition check	Check the trial file			
			1 min			Stop the centrifuge		
		0:45	1 min	Medical Condition check	Create New Trial with MoCap	Adjust radius	Stop recording sled signal	
			12 min	Rest		Move cables on centrifuge	Create new record file	ERT_X_VIC_CS
				Cover subject with a blanket				
				Camera calibration (Sweep the wand)	Start Camera Calibration + Check			
				Camera set origin	Start Camera set origin			
				Remove the blanket				
			2 min	Push sledge and subject's shoulders and Measure voltages at Up and Down positions	Check Markers and Reflections (full range of motion)		Set voltage, Run & Check the motivation tool	
				Take photos for references	FP Signal Check			
							Start recording sled signal	
		1:00	1 min				Start the centrifuge	
			1 min	Medical Condition check				
			10 s	Stay at Midpoint position (arms downward)	Check force plates	Adjust RPM & Announce 1 g		
		1:03		Stay at UP position	Start Trial 4 (MoCap)			ERT_X_VIC_CS01
			5 s	Place both arms downward for 5 s.				
			5 s	Place both arms on chest for 5 s.				
			5 s	Place both arms up for 5 s.				
				Stay at DOWN position (90deg flexion)				
			5 s	Place both arms downward for 5 s.				
			5 s	Place both arms on chest for 5 s.				
			5 s	Place both arms up for 5 s.				
	1:04	30 s	Rest	Stop Trial 4				
		1 min	Medical Condition check	Check the trial file				
				Create New Trial with MoCap				
	1:06			Start Trial 5 (MoCap)		Select Profile Signal2	ERT_X_VIC_CS02	
		1 min				Start 1min Profile Signal2 (The signal with 2s pause)		
		20 s	With arms down, Squat for 5 rep.					
		20 s	With arms on chest, Squat for 5 rep.					
		20 s	With arms up, Squat for 5 rep.					
	1:08	30 s	Rest	Stop Trial 5		Stop 1min Profile Signal2		
		1 min	Medical Condition check	Check MoCap file				
				Create New Trial with MoCap				
	1:10			Start Trial 6 (MoCap)		Select Profile Signal3	ERT_X_VIC_CS03	
		1 min				Start 1min Profile Signal3 (Continuous signal)		
		20 s	With arms down, Squat for 10 rep.					
		20 s	With arms on chest, Squat for 10 rep.					
		20 s	With arms up, Squat for 10 rep.					
	1:12	30 s	Rest	Stop Trial 6		Stop 1min Profile Signal3		
		1 min	Medical Condition check	Check the trial file				
	1:14	1 min				Stop the centrifuge		
		1 min	Help the subject exit			Stop recording sled signal		
Part 3	Preparation (10 min)	1:15	1 min	Rest	Start Vicon PC		Move the computer & USB	
			1 min		Turn on Vicon Box		Set up at control station	
			1 min		Check Camera Setup		Measure & Mark feet position on force plates	
			1 min		Turn on FP Box		Open "Acknowledge" and Create new file	ERT_X_VIC_CO
			1 min		Start Vicon Nexus			
			30 s		Check Session (F2)			
			30 s		Zero Level FPBox			
			1 min		FP Signal Check			
			1 min		Check harness, 12 markers, 3 accelerometers (power on) and Take photos for references	DV Cam Signal Check		
			1 min		Weigh the subject with equipment			
			1 min	Transit to control station				

Part	Activity	Time	Duration	Subject	Vicon System	Centrifuge	Motivation Tool / Profile Signal	File Name
Part 3	Control Station (15 min)	1:25	1 min	Subject Enters Control Sled				
			2 min	Take photos for references	Check Markers and Reflections (full range of motion)			
			2 min	Push Subject's shoulders and Measure Voltage at squat Up and Down positions	Check force plates		Set voltage, Run & Check the motivation tool	
			1 min	Medical Condition check			Start recording sled signal	
		1:31			Start Trial 1 MoCapControl		Select Profile Signal2	ERT_X_VIC_CO1
			1 min				Start 1min Profile Signal2 (The signal with 2s pause)	
			1 min	Squat for 15 rep.				
		1:33	30 s	Rest	Stop Trial 1		Stop 1min Profile Signal2	
			1 min	Medical Condition check	Check the trial file			
					Create New Trial with MoCap			
		1:35			Start Trial 2 MoCapControl		Select Profile Signal3	ERT_X_VIC_CO2
			1 min				Start 1min Profile Signal3 (Continuous signal)	
			1 min	Squat for 30 rep.				
		1:37	30 s	Rest	Stop Trial 2		Stop 1min Profile Signal3	
			1 min	Medical Condition check	Check the trial file		Stop recording sled signal	
	1 min	Help the subject exit						

## Appendix B: Body Measurements of Test Subjects

Body Segments		Subject ID								
		A	C	N	P	F	H	R	S	
Arm Data (cm)	Perimeters	Shoulder	31	31	29	31	34	45	37	36
		Mid-upper arm	26	25	24	25	28	37	30	29
		Elbow	24	23	22	24	25	31	28	27
		Thick part of forearm	24	24	22.5	25	26	31	27	28.5
		Wrist	18	16	15	16	16	19	17.5	18
		Base of thumb	24	22	20	22	25	26	25.5	24.5
		Knuckles	19	17	16	19	18	20	20	19.5
		Fingernails	16	13	14	14	13	17	15	15.5
	Widths	Wrist	6.5	6	6	6	6	7	7	6.5
		Base of thumb	10	9	8	9	11	12	12	10
		Knuckles	8	7	7	7	8	9	9	8
	Segment Lengths	Fingernails	6	6	5	5	6	8	7	5
		Shoulder to mid-upper arm	14	14	12	14	12	15	13	12
		Mid-upper arm to elbow	9	11	10	9	9	11	13	11
		Elbow to thick part of forearm	7	8	7	6	9	7	7	7
		Thick part of forearm to wrist	19	18	17	19	21	22	20	20
		Wrist to base of thumb	5	4	4	4	4	5	4	5
		Base of thumb to knuckles	7	6	6	6.5	6	5	4	7
Knuckles to fingernails		8	7.5	8	7.5	8	9	10	9	
Leg Data (cm)	Perimeters	Hip joint center	44.5	42	45.5	46	42	52	43	50.5
		Depth at hip joint center	20	20	18	20	22	24	22	24
		Crotch	59	59	62	59	59	63	63	61
		Mid-thigh	53	52	48	52	45	52	56.5	51
		Knee joint center	35	37	31	34.5	34	38	37	37
		Maximum calf perimeter	38	36	35.5	33	39	42	40	39
		Ankle joint center	23	25	21.5	22	24	23	24	25
		Heel	32	31	29	29	34	35	35	35
		Arch	26	23	23	21.5	27	27	26	26.5
		Ball	24	20	21	22	23	24	24	24
	Widths	Toenails	18	17	15	17	16	20	20	20
		Heel	12	12	11	11	12	12	12	12
		Ball	9	9	10	10	9	10	11	11
	Segment Lengths	Toenails	9	6	6	7	6	8	8	7
		Hip joint center to crotch	17	18	12	15	25	18	20	18
		Crotch to mid-thigh	12	16	14	18	14	13	20	11
		Mid-thigh to knee joint center	23	18	18	19	13	22	15	20
		Knee joint center to maximum calf perimeter	13	14	13	12	16	11	17	11
Maximum calf perimeter to ankle joint center		23	27	20	22	22	27	24	27	
Ankle joint center to heel		10	7	8	10	10	12	10	11	
Heel to arch		13	5	10	10	11	12	13	10	
Arch to ball	8	7	8	9	9	10	9	10		
Ball to toenails	5	4	4	3	5	4	6	4		
Torso Data (cm)	Perimeters	Top of head	45	48	51	45	51	58	56	52
		Above ear	56	57	55	57	59	61	61	60
		Beneath nose	47	47	49	46	48	53	48	51
		Acromion	38	35	34	35	38	43	38	40
		Underarm	87	86	86	90	93	111	105	96
		Nipple	89	90	91	89	91	105	99	93
		Lowest front rib	74	71	71	78	86	99	91	86
		Navel	78	74	70	73	90	100	89	84
		Hip joint center	89	84	91	91	84	104	86	101
	Widths	Acromion	13	12	11	12	13	14	13	13
		Underarm	30	32	29	34	33	38	34	36
		Nipple	28.5	29	29	29	29	35	32	32
		Lowest front rib	27	25	24	26	29	32	30	29
		Navel	25	28	25	24	32	32	29	30
		Hip joint center	32	31	30	32	33	36	35	34
	Segment Lengths	Top of head to above ear	9	8	9	12	12	9	13	12
		Above ear to beneath nose	6	5.5	6	7	6	5	6	7
		Beneath nose to acromion	11	8.5	11	9	8	11	10	9
Acromion to underarm		10	14	9	10	8	10	11	8	
Underarm to nipple		9	7	9	10	16	11	9	13	
Nipple to lowest front rib		14	14	10	11	9	12	9	10	
Lowest front rib to navel	9	8	11	9	11	13	14	13		
Navel to hip joint center	5	5	10	8	2	5	7	5		

## Appendix C: Masses and Centers of Masses of Test Subjects' Body Parts

calculated by using the MICRO-G Inertia software developed by Rebecca Sampson and Rachel Ellman  
at the Massachusetts Institute of Technology in July 2005

Body Segments	Subject A			Subject C			Subject N			Subject P		
	Mass (kg)	Length (m)	Center of Mass (m)	Mass (kg)	Length (m)	Center of Mass (m)	Mass (kg)	Length (m)	Center of Mass (m)	Mass (kg)	Length (m)	Center of Mass (m)
1 Upper Arm	1.44996	0.23	0.104878	1.47797	0.25	0.11935	1.17039	0.22	0.09949	1.39821	0.23	0.104295
1 Lower Arm	0.9865	0.26	0.106618	0.916024	0.26	0.101802	0.698984	0.24	0.088043	0.905578	0.25	0.095386
1 Palm	0.376466	0.12	0.057168	0.2673	0.1	0.048526	0.21833	0.1	0.047787	0.321136	0.105	0.054771
5 Fingers	0.178959	0.08	0.039602	0.094134	0.075	0.030671	0.12935	0.08	0.041569	0.177905	0.075	0.033937
1 Thigh	10.5936	0.52	0.239113	10.9306	0.52	0.247342	8.62476	0.44	0.190335	10.9357	0.52	0.238589
1 Calf	3.39637	0.36	0.155825	3.82015	0.41	0.178651	2.68597	0.33	0.146072	2.64818	0.34	0.145486
1 Foot	1.68779	0.31	0.151669	0.743208	0.19	0.077602	0.99793	0.26	0.111912	1.06811	0.29	0.124232
5 Toes	0.119213	0.05	0.017047	0.088865	0.04	0.021164	0.055959	0.04	0.021491	0.057263	0.03	0.015008
Torso and Head	26.9447	0.73	0.434032	24.4737	0.7	0.406743	27.5311	0.75	0.437375	28.3368	0.76	0.454171
<b>Total Mass of Subject</b>	<b>64.5224</b>			<b>61.1502</b>			<b>56.6945</b>			<b>63.3611</b>		

Body Segments	Subject F			Subject H			Subject R			Subject S		
	Mass (kg)	Length (m)	Center of Mass (m)	Mass (kg)	Length (m)	Center of Mass (m)	Mass (kg)	Length (m)	Center of Mass (m)	Mass (kg)	Length (m)	Center of Mass (m)
1 Upper Arm	1.52372	0.21	0.09403	3.23937	0.26	0.11425	2.17805	0.26	0.117364	1.81805	0.23	0.103382
1 Lower Arm	1.20825	0.3	0.114741	1.64475	0.29	0.109656	1.12462	0.27	0.095714	1.32036	0.27	0.106518
1 Palm	0.24887	0.1	0.046534	0.253037	0.1	0.044236	0.159936	0.08	0.037543	0.412531	0.12	0.058416
5 Fingers	0.083144	0.08	0.03385	0.113351	0.09	0.039290	0.119171	0.1	0.042585	0.227536	0.09	0.043829
1 Thigh	10.3658	0.52	0.243115	12.1771	0.53	0.235556	13.5424	0.55	0.265712	10.7403	0.49	0.218796
1 Calf	3.78109	0.38	0.169988	4.07204	0.38	0.158415	4.36291	0.41	0.178583	3.81451	0.38	0.164329
1 Foot	1.80665	0.3	0.137024	2.09188	0.34	0.152036	1.92827	0.32	0.135054	1.82036	0.31	0.128248
5 Toes	0.145391	0.05	0.022334	0.127161	0.04	0.019192	0.151736	0.06	0.031475	0.121056	0.04	0.021484
Torso and Head	31.5091	0.72	0.430876	44.4625	0.76	0.461586	37.7844	0.79	0.469524	34.3993	0.77	0.457043
<b>Total Mass of Subject</b>	<b>69.8349</b>			<b>91.9</b>			<b>84.9186</b>			<b>74.9487</b>		