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EFFECT OF FOOT ADDITIONAL MASS ON THE CLINICAL ANGLES OF KNEE EXTENSION EXERCISE

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ABSTRACT

This study investigates the effect of foot additional mass on the abduction and internal rotation knee angles during knee extension exercise. Three subjects (two male and one female) performed four sets of ten repetitions of the knee extension exercise for the right leg. For the first set, the subject performed the exercise with no additional weight. For each set after, weight was added around the subject's right foot and the subject was allowed a rest period before beginning the next set. The weights for sets 1, 2, 3, and 4 were 0.00kg (no additional weight) ,0.82kg, 1.64kg, and 2.27kg respectively. The subject's motion during the knee extension exercise was tracked by utilizing VICON motion analysis system to capture position data of markers placed on the femur and tibia. This data was filtered with a low pass Butterworth filter and used to create tibial and femoral coordinate systems' unit vectors. These unit vectors were used to determine the knee joint coordinate system. The joint coordinate system was then used to calculate the clinical angles: knee extension, abduction, and internal rotation. After averaging ten repetitions for each set (additional mass), the effect of additional mass on clinical angles was reported. The data showed that each subject had a differing natural motion when performing the exercise. The amount of internal rotation during the first 90^0 to 30^0 of flexion can vary between subjects. However, the screw-home mechanism is observed, i.e. tibia externally rotates with respect to femur as the knee extends. This is true for all subjects. On the other hand, the abduction of the tibia varies greatly between subjects. This finding has been acknowledged in the literature. Although the initial and final values for the clinical angles were affected when additional weight was added, the amount was insignificant and unpredictable.

1. INTRODUCTION

The knee extension exercise is a common rehabilitation exercise. It is performed from sitting position, and it consists of an extension from 90 degrees of flexion to full extension. Femur is considered at rest. The quadriceps muscle is the extensor muscle in this exercise. The screw-home mechanism (tibia rotates externally with respect to femur) occurs during the knee extension. The screw-home mechanism is important to understand the stability of the knee when it extends fully as it shows the signs of a healthy knee.

Knee extension is a fundamental movement involved in many daily activities such as walking, running, and jumping. It also plays a crucial role in sports performance, particularly in activities that require explosive lower body movements. Investigating knee extension gives insight into the strength and function of the quadriceps muscle and the knee joint. The knee extension exercise can be conducted with additional weights to help increase the leg strength. It is important to understand how added weights affect exercise. Knee extension can also be affected by various factors such as ACL tears or bone deformities, making it important to have a baseline understanding of what a normal extension looks like.

Motion capture and in vivo testing can be used to obtain data on marker motion during knee extension. This data can be used to analyze the movement patterns of the knee joint and identify any abnormalities or compensations that may be present. With motion capture technology there is no need for invasive procedures such as percutaneous puncture. It can also recreate complex movement in an accurate way, has little to no latency issues, and is safer to perform for experiments.

Methods for calculating knee extension include the Cardan angle method and the helical axis method. "A rotation matrix has nine elements; however, there are only three rotational degrees of freedom. Therefore, a rotation matrix contains redundant information. Euler angles express the transformation between two [Coordinate Systems, CS's] using a triad of sequential rotations." [2]. "A sequence with the same first and third axes (e.g., XYX or ZXZ) is usually called an Euler sequence, while a sequence involving all three is called a Cardan sequence (e.g., XYZ or ZXY). The Euler angles may also be expressed as space-fixed, in which all the rotations occur about the axes of a CS that is fixed in space (may or may not be the initial CS)." [2]. "An important issue with the Euler/Cardan angles is the existence of a mathematical singularity (often called gimbal lock). This occurs when the second rotation is zero (Euler sequences) or 90 degrees (Cardan sequences). One can avoid singularities by using a quaternion (e.g., Euler parameters) instead of Euler angles, but quantities are difficult to interpret physically." [2]. While Euler angles can be used for this experiment the limitations of it make it more difficult to use for the analysis of the knee extension [2]. "The helical axis concept is based on a classical result in kinematics due to Chasles, stating that any rigid body transformation can be considered as the result of a translation along an axis and a uniform rotation through an angle about the same axis. This description can refer either to a finite rigid body transformation between two distinct poses or to an infinitesimal transformation, thereby characterizing the differential change along a curve of rigid body transformations. While the second is commonly known as the instantaneous helical axis (IHA), the first interpretation is appropriately denoted as finite helical axis (FHA), which provides a rough estimate of the IHA as the two poses approach each other." [3]. "However, it is well known that the FHA is highly sensitive to noise in the two sample poses involved and its computation becomes numerically unstable for small differences, while on the other hand using too large a difference yields only a bad approximation to the IHA" [3]. Some experimental works, including this one, analyzed the knee joint and the flexion angles using joint coordinate systems. The joint coordinate system is a widely used method for calculating the motion of the knee joint during knee extension. "The Joint Coordinate System (JCS) was first introduced by Grood and Suntay [1]. It was developed out of the need to describe human joint motion in a language understandable to both clinicians and engineers. Until then, most experimental studies of joint motion had only presented data in terms of relative rotational motion between the articulating bones of the joint using Euler angles as the rotational position coordinates or the screw (helical) axis. However, the former is dependent on the order in which the translations and rotations occur, and the latter is conceptually difficult to visualize and understand" [1]. "The JCS is a desirable system as it is easily understood. Since its introduction, it has been used as the International Society of Biomechanics (ISB) recommended coordinate system in numerous biomechanical studies for a variety of joints. For knee studies, flexion angles have been commonly presented in graphical format, typically showing flexion angle versus either internal–external rotation angle or translations" [4]. Joint coordinate systems are what makes analyzing all the knee flexion angles possible and simpler to help visualize and understand what's going on during the exercise [4]. While the JCS is preferred it does have limitations, "It is often mentioned that the JCS is advantageous over Euler angles because JCS is sequence independent. This statement may not be entirely accurate, as there is indeed a sequence that is embedded in the choice of the axes" [4]. These methods differ in their level of accuracy and complexity, and the choice of method depends on the specific research question and available resources. The joint coordinate system is the method that was chosen for this experiment.

2. EXPERIMENTAL PROTOCOL

2.1 Instrumentation

The experimental data was gathered using a VICON (Vicon Motion Systems Ltd, Oxford UK) motion analysis system consisting of ten infrared cameras circularly positioned around the room, Fig. 1. The cameras were used to capture the light reflected from the markers placed on the subject while performing the task. The VICON Nexus 2.14 software system was used to record all marker locations at rate of 100 Hz and later provide the coordinates of each marker.

Figure 1 shows the experimental setup involved the utilization of motion capture cameras, strategically positioned to capture precise movements of the subject. The camera positions were carefully selected to ensure comprehensive data collection and accurate analysis of the experiment.

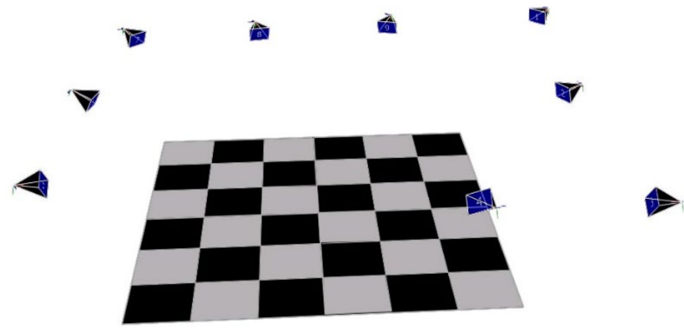

FIGURE 1: CAMERA POSITIONING.

2.2 Experimental Set-up

Before working with the subject, the room should be cleared of any light-reflecting objects as well as any other big sources of light. In addition, the cameras need to be calibrated using Nexus 2.14 and the origin needs to be set. Once this is done, the subject can be prepared. The subject will need to wear close-fitting garments such as leggings or short shorts as well as a short or tucked-in shirt and socks. The subject will then proceed to perform some stretching exercises in order to loosen up his or her muscles. The stretching exercises should consist of standing hamstring stretching, hamstring/calf stretching, calf stretching, inner thigh stretching, and thigh stretching. For this particular experiment, the following exercises were performed: releases of hamstring, gastrocnemius, and popliteus; fascial glide of the back of thigh and back of calf; joint mobilization for knee traction, mobilization, and external rotation of tibia; overpressures at knee extension, prone extension, sitting extension; stretches to increase knee extension; knee extension strengthening exercises; and weight-bearing exercises. The markers will then be attached to the subject using double-sided tape; for that reason, baggy clothes should be avoided as they could potentially block or move the markers. It must be noted that using fabric to which the double-sided tape can better adhere itself such as nylon or wearing skin-revealing clothing such as small shorts can prove to be more efficient and diminish the use of unrelated marker movement. As for marker placement, it shall be done while the knee is in flexion, but the subject may extend the leg, stand, or rotate the leg in any manner that can help determine the best positioning of the markers relative to the landmarks chosen. The subject will then proceed to sit on a stool placed by the previously set origin such that his/her right foot is positioned on the positive side of the x-axis and the right knee extension will be performed on the positive y-axis. It must be noted that the stool or flat surface used must be tall enough for the subject's leg to be suspended; in addition, a wedge-like object should be used to elevate the knee until there is a natural ninety-degree angle of flexion approximately. As a final part of the set-up, a heavy object of any kind should be placed touching the heel of the foot in its relaxed position to ensure every trial is done relatively from the same starting point. The knee extension exercise will consist of four steps: positioning of the foot, knee extension, pause in extension, and knee flexion. The whole process does not need to follow a predetermined tempo but will instead be done at a comfortable mostly constant pace for the subject. The subject will start the knee extension from a natural placement of the legs and a relatively straightened back, perform the knee extension, pause for a couple of seconds in extension, and return to the starting position. The knee extension should be a fluid and stable motion, also, the pause in extension should be stably held without shaking. The following knee flexion will not bear much importance in the experiment so there are no constraints specified. Instead, the subjects need only to focus on their positioning to start the next knee flexion in a once again comfortable and stable manner from the natural hanging position since the objective is to perform about ten good cycles. For the purpose of this experiment, the subjects need to perform this procedure four times with increasing amounts of ankle weights. It must be noted that even though ankle weights were used, the weights were positioned on the foot to not alter the marker placements in the ankle. The first sequence should be done with no weight added while the following sequences have a relatively consistent increase amount of ankle weight per sequence. In this scenario, single-weight pouches of 0.409 kg each and a non-adjustable ankle weight of 2.234 kg were used. For the second sequence, two weight pouches were wrapped around the subject's right foot using Velcro. Next, the third sequence was done with four weight pouches wrapped around the right foot with Velcro. And the final fourth sequence was done with the non-adjustable ankle weight that was also attached to the right foot in similar fashion.

2.3 Marker Placement

Bone landmarks, anatomical locations where there is not much flesh between the bone and skin, are best used to track bone position. These landmarks are chosen based on the relative motion between the markers attached to the skin and the bone that is moving under the skin. The relative motion should be minimal to accurately track the bone movement. In this experiment, markers are placed on the right ankle, right tibia tuberosity, right knee condyles, and the right greater trochanter.

The drawback to using the tibial tuberosity landmark is that it is not in the same plane with the ankle markers and longitudinal axis of tibia. This alters the results for the flexion angle. This inaccuracy will be fixed by creating a virtual marker as described in a later section.

Figure 2 shows the marker placement. To ensure accurate tracking of lower limb movement during the experiment, reflective markers were placed on specific anatomical landmarks of the lower right leg. As depicted in the image, the markers were positioned on the lateral and medial ankles (RLAN, RMAN), lateral and medial knee condyles (RLKN, RMKN), right tibia tuberosity (RTTP), and right greater trochanter (RGTR) allowing for precise data capture of joint angles and movement patterns.

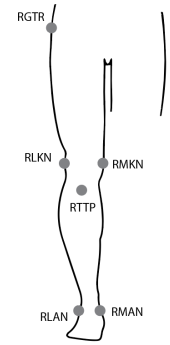

FIGURE 2: RIGHT LEG – NECESSARY MARKER PLACEMENT.

The markers that are necessary to create the unit vectors that will describe the body-planes for the tibia (i, j, k) and femur (I, J, K) are shown in Fig. 3. For the tibia these markers include the Right Medial Ankle (RMAN), Right Lateral Ankle (RLAN), and Right Tibial Tuberosity (RTTP). For the femur these markers include the Right medial knee (RMKN), right lateral knee (RLKN), right greater trochanter (RGTR).

The marker position data is motion captured with instrumentation mentioned previously and the raw coordinates of each marker are put through a Butterworth filter before being used to calculate the body-plane unit vectors for the tibia and femur.

2.4 Body-Fixed Planes

With three markers on each bone (femur and tibia) the frontal plane in the anatomical position of tibia and femur can be constructed. The origin is set so that the positive direction is rightward in the *x*-direction, anterior in the *y*-direction, and upward/proximally in the *z*-direction.

For the calculation of the position vector representing the x-direction of the tibia plane, markers that are aligned in that direction will be used. The position vector of the marker that is positioned in a less positive *x*-direction is subtracted from the position vector of the marker in a more positive *x*-direction. This process is used for the calculation of the position vector representing the *z* direction of the tibia plane. Since *z* is more positive towards the proximal direction, the position vector of one of the ankle markers is subtracted from the position vector of the marker on tibial tuberosity. Marker RLAN is used for this calculation, but RMAN can be used.

$$\overrightarrow{BC_T} = \overrightarrow{RLAN} - \overrightarrow{RMAN}, \quad \overrightarrow{CA_T} = \overrightarrow{RTTP} - \overrightarrow{RLAN} \tag{1}$$

This process is completed for the femur. However, CA and CB are based on the femur markers.

$$\overrightarrow{BC_F} = \overrightarrow{RLKN} - \overrightarrow{RMKN}, \quad \overrightarrow{CA_F} = \overrightarrow{RGTR} - \overrightarrow{RLKN} \tag{2}$$

The line that connects points A and B will complete this plane but will only be used for visualization purposes. It is also important to note that the frontal plane of the femur in the anatomical position is a horizontal plane for your knee extension exercise since the subject is sitting upright.

Figure 3 shows a body plane that was constructed for both leg segments by performing vector analysis on the 3D position data from the reflective markers.

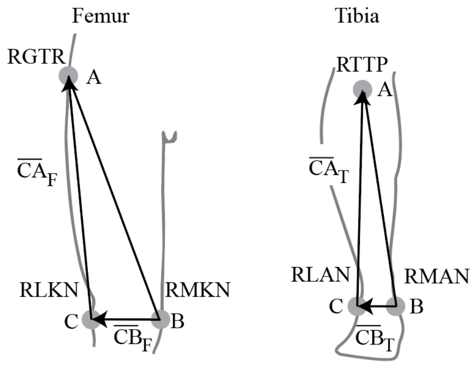

FIGURE 3: BODY PLANES – FEMUR AND TIBIA.

2.5 Body-Fixed Plane Unit Vectors

The unit vectors in the $\hat{I}$, $\hat{J}$, $\hat{K}$ directions for the femur and the $\hat{\imath}$, $\hat{\jmath}$, $\hat{k}$ directions for the tibia can be calculated using the previously created body planes. For the tibia, the process is as follows. The unit vector $\hat{\imath}$ is calculated by normalizing $\overrightarrow{BC_T}$, $\hat{k}$ by normalizing $\overrightarrow{CA_T}$, and $\hat{\jmath}$ by normalizing the cross product of $\hat{k}$ and $\hat{\imath}$. The same process is done for the femur.

Figure 4 shows unit vectors for each leg segment that are created using the body plane vectors. $\hat{I}$, $\hat{J}$, $\hat{K}$ are the femoral unit vectors and $\hat{\imath}$, $\hat{\jmath}$, $\hat{k}$ are the tibial unit vectors.

$$\hat{\imath} = \overrightarrow{BC_T} \,/\, \left|\overrightarrow{BC_T}\right|, \hat{k} = \overrightarrow{CA_T} \,/\, \left|\overrightarrow{CA_T}\right|, \hat{\jmath} = (\vec{k} \times \vec{\imath}\,)/\left|\vec{k} \times \vec{\imath}\right| \quad (3)$$

$$\hat{I} = \overrightarrow{BC_F}/\left|\overrightarrow{BC_F}\right|, \hat{K} = \overrightarrow{CA_F}/\left|\overrightarrow{CA_F}\right|, \hat{J} = (\vec{K} \times \vec{I}\,)/\left|\vec{K} \times \vec{I}\right| \quad (4)$$

2.6 Tibia Body-Fixed Planes Correction

The tibia tuberosity has a greater global Y-direction value when completely vertical compared to the right lateral ankle. This causes an issue with the tibia body-plane since the plane will be titled downward such that $\hat{\jmath}$ will not be parallel to the ground. Instead, it will be pointing toward the negative global Z-direction. This affects the flexion angle of the exercise since the $\hat{\jmath}$ *and* $\hat{J}$ will not align at full extension and will show a flexion greater than 90^0 when the tibia is completely vertical in the global Z-direction and the femur is completely horizontal in the global Y-direction.

The error can be corrected by virtually moving the RTTP marker along the $-\hat{\jmath}$ direction such that it will align in with RLAN in the global Z direction at full extension. Full extension is chosen simply because for each set of the experiment, there may be inconsistencies of the initial flexion angle, but each subject will reach approximately 0^0 of flexion across all repetitions of the exercise. This would produce a position vector between these two markers that is more representative of the orientation of the tibia and would result in $\hat{\jmath}$ being correctly oriented.

The distance along $-\hat{\jmath}$ that RTTP marker should be moved is l. This distance is unknown since $-\hat{\jmath}$ is not pointing parallel to the global Z direction at full extension. However, an acceptable estimation of l would be the physically measured length from the top of the tibia tuberosity and a line drawn proximally from the lateral ankle to the lateral knee. This can also be understood as approximately half of the thickness of the lower leg in the sagittal plane. This thickness is then multiplied by -$\hat{\jmath}$ and subtracted from the RTTP coordinates.

$$L = \overrightarrow{RTTP_z} - \overrightarrow{RLAN_z},\ V = RTTP - l * \hat{\jmath} \quad (5)$$

This will shift the physical marker posteriorly to create a virtual marker, V, that is inside the leg and will align with the right ankle at full extension. This distance can be measured using a physical measuring device or motion capture software. V must be used to create the corrected tibia body-plane by replacing RTTP in Eq. (1).

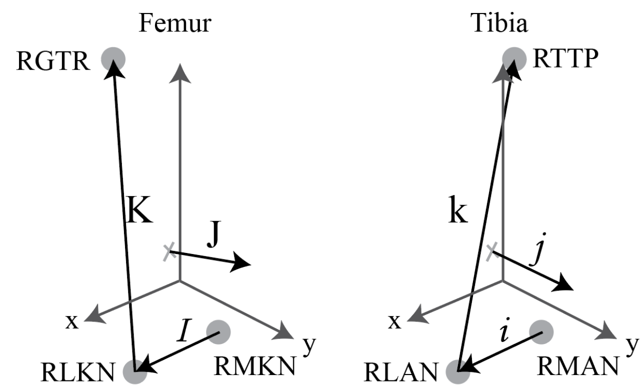

FIGURE 4: RIGHT LEG – UNIT BASE VECTORS.

2.7 Joint Coordinate System

Grood and Suntay [1] proposed a method of describing the rotational and translational motion between two bodies that would coincide with the clinical rotation and translational motion terminology used by today's physicians. This method included using the previously created unit vectors for two bodies A and B.

For the relative rotational and translational motion between Body A and Body B, Grood and Suntay [1] created a local coordinate system for each body to define where the origins OA and OB placed on each body. A second coordinate system using nonorthogonal unit base vectors e_1, e_2 and e_3 are also used, where e_1 and e_3 are body fixed axes on Body A and Body B, respectively. When there is no relative rotation or translation between the bodies, e_1 is pointed toward the positive $\hat{I}$ directions and e_3 is directed in the positive $\hat{k}$. e_2 is a floating axis, F, that is orthogonal to both e_1 and e_3. It is initially pointed in the global

Y-direction when there is no relative motion between Body A and Body B.

$$e_1 = \hat{I},\ e_3 = \hat{k}\ ,\ e_2 = F = \frac{e_3 \times e_1}{|e_3 \times e_1|} \tag{6}$$

where e_1^r and e_3^r are reference lines to calculate the relative rotations of Body B to Body A. These reference lines are chosen by convenience to the application.

$$e_1^r = \hat{K}\ ,\ e_3^r = \hat{\imath} \tag{7}$$

The angle between the floating axis, e_2, and e_1^r is α and represents the relative rotation of Body B compared to Body A. The angle between e_3^r and the floating axis is γ and is the rotation of Body B about its z axis. The angle between e_1 and e_3 is β and is the rotation of body B about the floating axis. These angles are calculated using the following relations:

$$\sin(\alpha) = e_2 \cdot e_1^r\ ,\ \sin(\gamma) = -e_2 \cdot e_3^r\ ,\ \sin(\beta) = e_1 \cdot e_3 \tag{8}$$

The vector that describes the relative translation between two specified points on each body, PA and PB is H. However, this will not be used in this study.

2.8 Knee Extension Exercise Joint Coordinate System

For applications of the joint coordinate system to the knee extension exercise, Body A is the femur and Body B is the tibia. e_1 is the body fixed axis in the femur that points from the medial right knee to the lateral right knee. Thus, is equal the unit base vector $\hat{I}$. e_3 is the body fixed axis that points proximally from the tibia tuberosity and is equal to the unit base vector $\hat{k}$.

e_2 is the floating axis, F. When sitting during the knee extension exercise, the $\hat{I}$ and $\hat{k}$ directions are unchanged compared to their anatomical positions, so the direction of F is also unchanged. During the knee extension exercise, $\hat{k}$ rotates about $\hat{I}$ and instead of pointing into the positive global Z direction, $\hat{k}$ will begin pointing in the negative global Y direction. Due to this, F will also rotate about $\hat{I}$. The reference line e_1^r is, chosen by convenience [1], equal to $\hat{J}$

$$e_1 = \hat{I}\ ,\quad e_3 = \hat{k}\ ,\quad e_2 = F = \frac{\hat{k} \times \hat{I}}{|\hat{k} \times \hat{I}|} \tag{11}$$

2.9 Clinical Angles

The clinical angles that are calculated using the joint coordinate system are the flexion, abduction, and internal rotation of tibia relative to femur. Flexion of the lower leg is the angle between the floating axis and the K direction minus 90^0.

$$\sin(\alpha) = -e_2 \cdot K \tag{12}$$

At full extension $\alpha = 0^0$, and for hyperextension $\alpha < 0^0$. Using Eq. (12), however, has limitations when the knee joint proceeds into flexion past 90^0. In this case, the data will become inverted, which is an incorrect representation of the experiment. This is not an issue for this experiment. The target initial flexion is 90^0.

The abduction of the leg is related to the angle β. It is the relative rotation between $\hat{k}$ and $\hat{I}$. It is important to understand that β is not the abduction angle. Since $\hat{I}$ and $\hat{k}$ are initially perpendicular to each other, β will be equal to 90^0. To calculate the abduction angle, 90^0 must be subtracted from β.

$$\cos(\beta) = \hat{I} \cdot \hat{k}\ ,\ \text{Abduction} = \beta - 90^0 \tag{13}$$

where abduction $\beta - 90^0 > 0^0$, no abduction $\beta - 90^0 = 0^0$, and adduction $\beta - 90^0 < 0^0$. The internal rotation angle, γ, is dependent on the direction of the floating axis and $\hat{\imath}$.

$$\sin(\gamma) = e_2 \cdot \hat{\imath} \tag{14}$$

where no internal rotation $\alpha = 0^0$, internal rotation $\alpha > 0^0$, and external rotation $\alpha < 0^0$.

3 DATA ANALYSIS

Once the marker position data is captured, it is filtered using a Butterworth Filter "forward" and "backward" to negate the phase shift that is caused by this type of filter. After this, the data is run though a MATLAB (The MathWorks, Inc., Natick, MA) code that calculates the clinical angles for each trial of each experiment. During this process, initial values for the clinical angles are used to create the tibia virtual marker. Then the tibial body-plane is recreated. Then the clinical angles are calculated. For this experiment, only the extension action of the exercise is analyzed. Since the marker data includes both the flexion and extension of the exercise, the code finds the points in time that leg was flexed and when it arrives at full extension and only plots these values. The code then plots the data from the flexion and extension parts of the exercise for all ten repetitions for that set and poly-fits the average of each extension.

Figure 5 shows the clinical angles for the 0.00kg experiment. All clinical angles have been plotted and the maximum and minimum values for flexion have been marked. They will be used to determine the points in time where the extension exercise began and was completed/

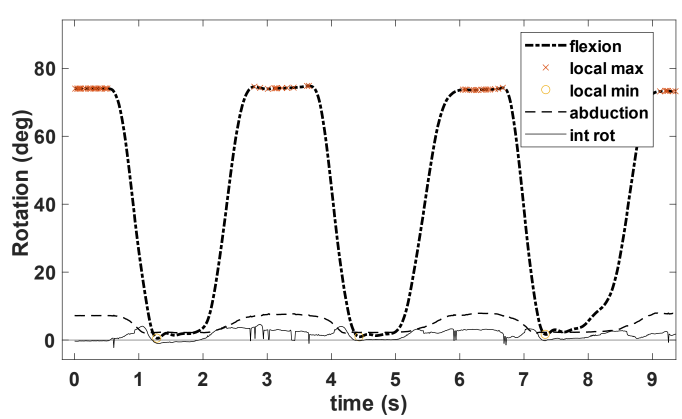

FIGURE 5: CLINICAL ANGLES V. TIME (0.00KG) MALE 1.

Figure 6 shows the absolute internal rotation of the tibia for the 0.00kg experiment. The ten trial extension data are overlayed on each other. The data is averaged and then poly-fitted. The poly-fitted line is plotted over the trial data.

Figure 7 shows the absolute abduction rotation of the tibia for the 0.00kg experiment. The ten trial extension data are overlayed on each other. The data is averaged and then poly-fitted. The poly-fitted line is plotted over the trial data.

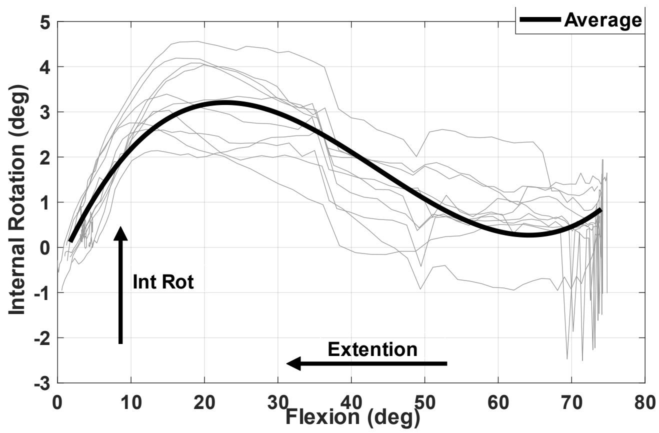

FIGURE 6: ABSOLUTE INTERNAL ROTATION (0.00KG) MALE 1.

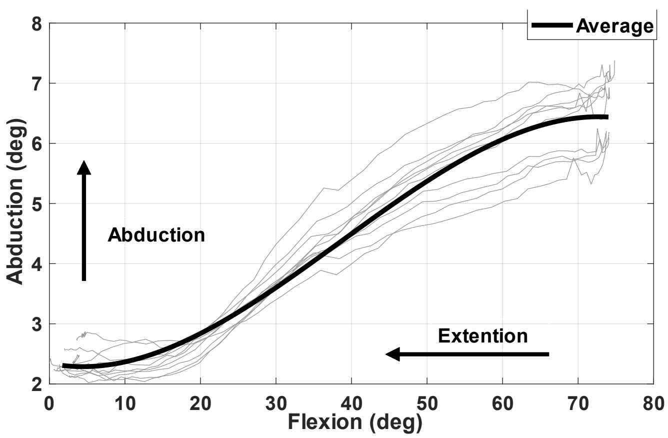

FIGURE 7: ABSOLUTE ABDUCTION (0.00KG) MALE 1.

It is important to note that the code first calculates the absolute flexion, extension, and abduction angles. The absolute data is dependent on the marker location and may not represent the actual clinical angles of the bones relative to each other. It is acknowledged that marker data placed on bone landmarks cannot show correct absolute clinical angles.

Figure 8 shows the poly-fitted averages of the absolute internal rotation of the tibia for the 0.00kg, 0.82kg, 1.64kg, and 2.27kg experiment. Internal rotation is positive.

The data that is useful from these graphs are the initial and final values of the clinical angles. When adding weight, the initial abduction or internal rotation angles may change. This can be caused by the torque of the weight on the subject's foot or by the natural response to prepare for the exercise.

Figure 9 shows the poly-fitted averages of the absolute abduction rotation of the tibia for the 0.00kg, 0.82kg, 1.64kg, and 2.27kg experiment. Abduction is positive.

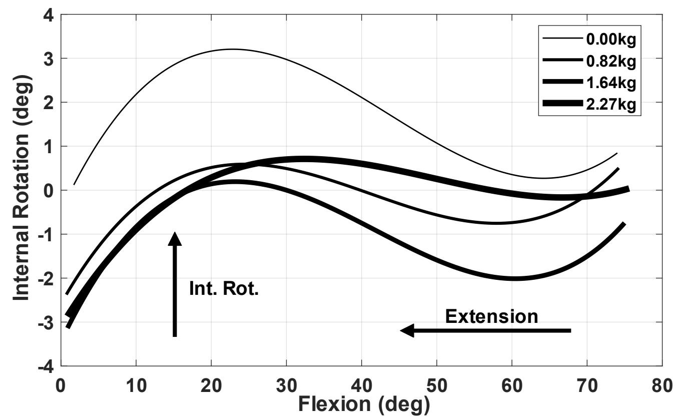

FIGURE 8: AVERAGE ABSOLUTE INTERNAL ROTATION MALE 1

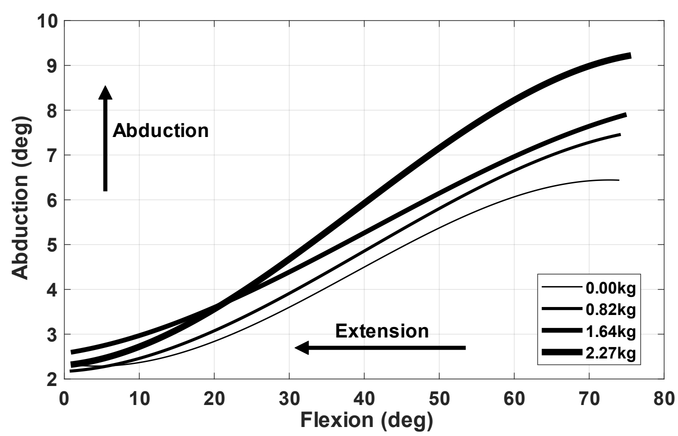

FIGURE 9: AVERAGE ABSOLUTE ABDUCTION MALE 1.

The displacements of the clinical angles are mostly unaffected by markers attached to the skin. As mentioned before, the marker data is not fully accurate since there is still some relative motion between the bone and the skin where the marker is placed. The average displacements from full extension of the abduction and internal rotation angles are plotted in one figure for each set of the experiment. Figure 10 shows the displacement poly-fitted averages of the absolute internal rotation and abduction of the tibia for the 0.00kg experiment in one plot.

Finally, the average displacements of the clinical angles for all trials in each experiment are then plotted in one figure, Figs. 11 and 12. Figure 11 shows the poly-fitted averages of the internal rotation displacement of the tibia for the 0.00kg, 0.82kg, 1.64kg, and 2.27kg experiment. Internal rotation is positive. Figure 12 shows the poly-fitted averages of the abduction displacement of the tibia for the 0.00kg, 0.82kg, 1.64kg, and 2.27kg experiment. Abduction is positive.

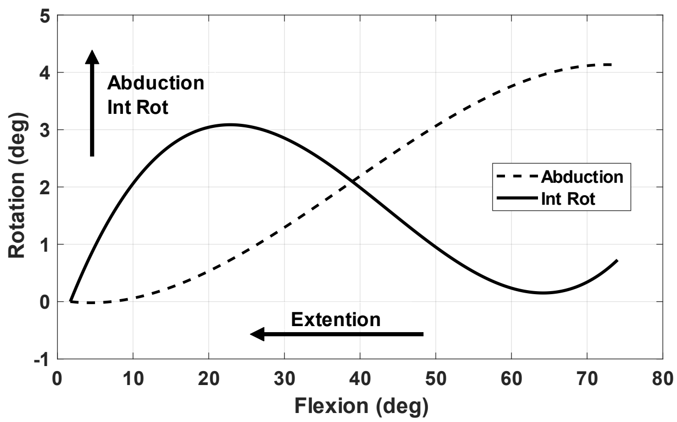

FIGURE 10: DISPLACEMENT OF CLINICAL ANGLES (0.00KG) MALE 1.

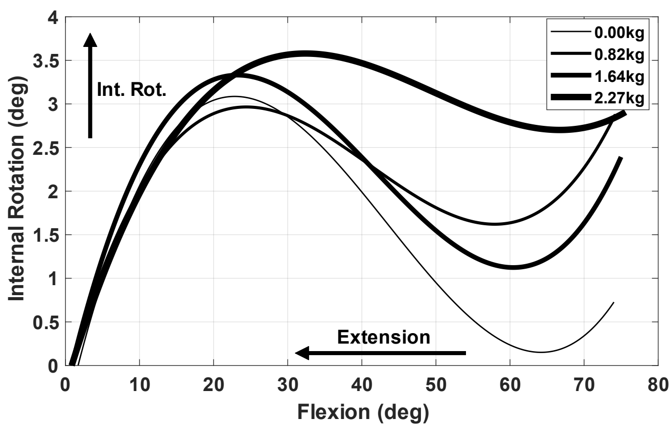

FIGURE 11: AVERAGE DISPLACEMENT: INTERNAL ROTATION MALE 1.

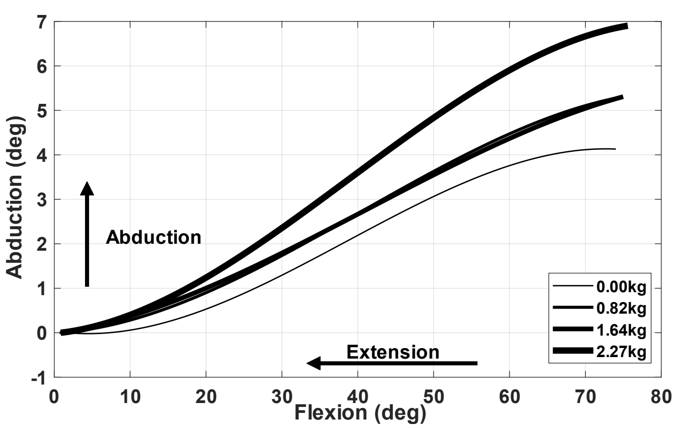

FIGURE 12: AVERAGE DISPLACEMENT ABDUCTION MALE 1.

4 RESULTS AND DISCUSSION

In this work, there were 3 subjects performing knee extension exercises. Each subject would perform 10 extensions of the knee for 4 different experiments. The 4 experiments included performing knee extension exercises without any weight added to the foot then by adding 0.82kg, 1.64kg and 2.27kg after 10 repetitions were completed with a period of rest between each experiment. The subjects included one female and two males.

Figure 13 shows the poly-fitted averages of the internal rotation displacement of the tibia for the 0.00kg and 2.27kg experiments for each subject. Internal rotation is positive.

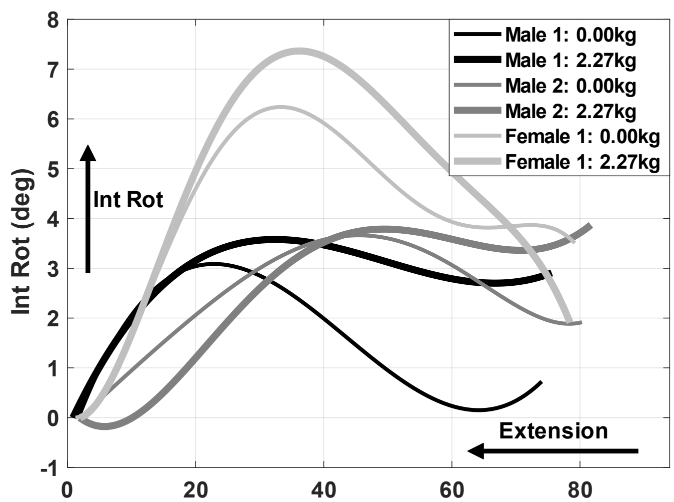

FIGURE 13: AVERAGE DISPLACMENT: INTERNAL ROTATION – ALL SUBJECTS (0.00KG & 2.27KG).

From the data there is not a correlation between male and female subjects' internal rotation values nor a correlation between male subjects. For the unweighted trials, Female 1 and Male 1 both show an initial increase in internal rotation of about 3^0 from their initial position before external rotating from the respective max value to 0^0. While Male 2 only exhibited an increase in internal rotation of about 1.5^0. Male 1 and Male 2 had an initial external rotation before internally rotating from 60^0 to 20^0 and then finally rotating externally for the remaining degrees of extension. Male 2's internal rotation value remained constant until about 30^0 when the Screw-home mechanism takes place. Female 1 performs a brief change internal rotation for the beginning of the exercise, then remained constant until following a similar pattern compared to the males. During the 2.27kg trials, Female 1 showed a break from the motion that was shown in the unweighted trials. Female 1 internally rotated until 40^0 of extension. The notable difference is that the female subject internally rotated 7.5^0 from the initial internal rotation. After comparing both experiments for the male subjects, the males did not break from the unweighted motion. However, during the 2.27kg experiment, the initial internal rotation increased by about 2.25^0 and only reached a maximum value 0.5^0 or less above the unweighted experiment. Despite these differences, all subjects show similar overall motions and external rotation before reaching full extension which aligns with the mechanics of the screw-home mechanism.

Figure 14 shows the poly-fitted averages of the abduction displacement of the tibia for the 0.00kg and 2.27kg experiments for each subject. Internal rotation is positive.

There also is no correlation between male and female, and male and male subjects' abduction displacement values but, contrary to the internal rotation, Female 1 and Male 1 have similar abduction motions and Male 2 is significantly different than the other subjects. Both Female 1 and Male 1 show a decrease in abduction over the course of the exercise. Male 2 first becomes more adducted before abducting again.

For Female 1 and Male 2, the initial abduction angle for the unweighted and 2.27kg experiments, were within 0.5^0 of each other. This was not true for Male 1 who saw an increase of 3^0 in the initial value when weight was added.

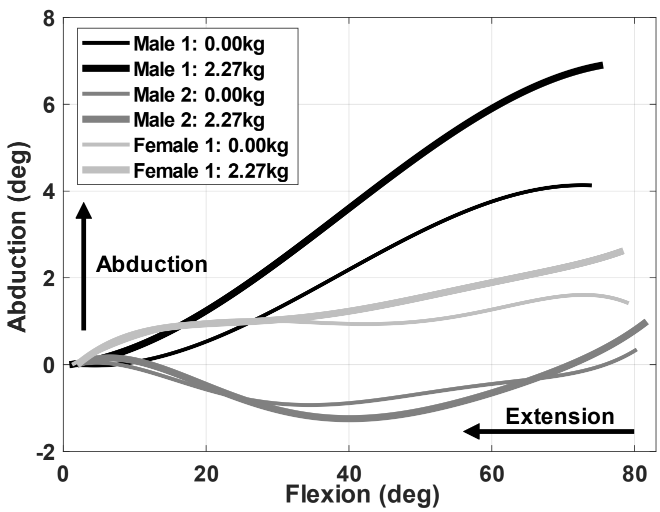

FIGURE 14: AVERAGE DISPLACMENT: ABDUCTION – ALL SUBJECTS (0.00KG & 2.27KG).

5 CONCLUSION

Three subjects performed the exercise 10 times, and the clinical angles were measured and averaged. The results showed that there was an insignificant and unpredictable change to the initial and final values of the clinical angles as weight was added for each subject. Additionally, the average displacements of the internal rotation and abduction for each subject individually also remained consistent throughout the 4 sets. Although the subjects' motions are significantly different between each other, the motion for each set for a specific subject followed a unique pattern. This can indicate consistency in the exercise's performance and the natural motion of that specific subject.

It is difficult to compare with other studies on knee extension exercises because many use 3D models or cadavers where the femur is artificially or physically unallowed to rotate. Studies that use live subjects also use methods like Euler angles to calculate the clinical angles which are subject to variation caused by selecting a rotation order. However, some conclusions can be made about the performance of the subject and the required effort.

In the research done by Shoemaker [5] the exercise was done where on cadaver bones where quadricep muscles were active or not present. When the muscles were stabilizing the tibia, the internal rotation of the tibia increased from the start of the extension before decreasing around 50^0 of flexion. This pattern can be seen in Female 1's experiments. It can be an indication that this individual used more of their quadriceps to stabilize their legs while performing the exercise. Shoemaker's research also showed that when the muscles were underutilized for a healthy individual, the subject had no change in internal rotation until about 40^0 of flexion where the tibia began to externally rotate. Both males exhibited this type of motion. The males' internal rotation remained constant until about 30^0 to 40^0 before externally rotating. It was also proven outside of this experiment that both males are capable of lifting heavier weight than Female 1, and Male 1 has weight training experience. It may be concluded that the amount of weight used in this experiment may not be significant enough to activate a stabilizing response from the quadriceps for the males.

In Ref. [6], they conclude that "…passive knee motion always involves internal rotation with flexion, there is no consistent pattern of ab/adduction." This study analyzed 12 healthy knees during knee extension and the amount of initial, final and the change in the abduction varied significantly between each subject. This is also the case for this experiment. Male 1 and Female 1 show a very similar motion of abduction, but the amount of abduction is almost threefold for Male 1 compared to Female 1. Male 2 had a significant dissimilarity between the other two subjects. Male 2's motion does resemble the research done by Wilson et al. [7] performed using a live subject. The subject became more adducted from 90^0 to about 50^0 of flexion, then increased in abduction. This was also consistent with the 3D model that they created and compared with. When comparing the abduction for Male 2 and Wilson et al.'s data [7], it shows the same increase in abduction of about 2.5^0 before returning close to the initial value after the 50^0 of flexion.

In conclusion, the amount of internal rotation during the first 90^0 to 30^0 of flexion can vary between subjects, but because of the Screw-home mechanism, the tibia must externally rotate. This is true for all subjects. On the contrary, the abduction of the tibia varies greatly between each subject and this finding has been acknowledged in other research papers.

Based on the findings of the research paper, adding weight to the foot during knee extension exercises does not have a significant effect on clinical angles. The study observed that even after adding 2.27kg of weight, the initial internal rotation during knee extension exercises increased by only 2^0 for the male subjects and decreased by about 1^0 for the female subject, Fig. 13. In reviewing all the experimental averages for Male 1's internal rotation displacement in Fig. 11, initial internal rotation increased as weight was added. Each experiment remained within 2^0 of the initial unweighted values which is not believed to be a significant change. Additionally, the study found that for Male 1's weighted experiments, the internal rotation values were equal during the final degrees of extension which is shown in

Fig. 8. This is also a similar case for tibial abduction during the weighted and non-weighted experiments, Fig. 9. The initial value for the abduction displacement only increased about 1^0 when 2.27kg were added for Male 2 and Female 1. Male 1, who had the most change to the abduction displacement overall, saw an increase of about 3^0, Fig. 14. Reviewing the experimental averages for Male 1's abduction displacement in Fig. 12, the initial abduction increased as weight was added. Each experiment remained within 3^0 of the initial unweighted values which is also not believed to be a significant change. For both the internal rotation and abduction, the natural motion of the subject remained consistent despite the added weight and initial increase to the clinical angle.

There are certain motions that are associated with healthy knee anatomy and motion capture of the subject's movement can be a noninvasive procedure to assess the health of a subject's knee. This study has important implications for clinicians and trainers who use knee extension exercises as a part of their rehabilitation or fitness programs. It suggests that the exercise can be performed consistently while using weight that requires low effort from the patient with the option of increasing the weight to recruit the quadriceps to assist with stability. The ability to have this option can lead to better outcomes in terms of rehabilitation and performance improvement.

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