Can Humans Axially Rotate Their Pelvis and then Thigh in Time to Avoid Landing on Their Greater Trochanter During a Sideways Fall?

A Preliminary Experimental Study and Computer Simulation Analysis of the Effects of Age, Strength, Gender, and Body Weight

Abstract

Fall-related injuries, and in particular hip fractures, are a leading cause of morbidity and mortality in the elderly population. We posited that it should be possible to rotate the pelvis, and counter rotate the thigh, during a sideways fall so as to avoid landing directly on the greater trochanter, thereby dramatically lessen the risk for a hip fracture. Experiments were conducted on two adult males, and simulations were conducted using ADAMS and muscle strength values from the literature to see how feasible this strategy is for various ages, strengths, genders, and body weights. The results show that for both genders and all ages and body weights it should be possible to make a 20° axial rotation of the pelvis, and 20^o counter-rotation of the thigh, in time to avoid landing on the greater trochanter during a sideways fall. However, a 30^o rotation only appears to be able to be reliably conducted by younger individuals of normal body weight. The project points up the dearth of data on internal and external hip muscle rotator strengths at any age. Future research should check whether individuals can actually learn to perform this injury avoidance maneuver in a real sideways fall.

1. Introduction

There are approximately 35 million people living in the U.S. who are over the age of 65 years (U.S. Census Bureau 2003). An injurious fall in an elderly individual can be devastating. Indeed, more elderly die from falls than die from motor vehicle accidents each year (CDC 1999). More than one-third of adults ages 65 years and older fall each year (Hornbrook 1994; Hausdorff 2001). Older adults are hospitalized for fall-related injuries five times more often than they are for injuries from other causes (Alexander 1992). The most costly fall-related injury is a hip fracture because it carries the risk for serious sequelae, including bone infection and pneumonia, both of which can be fatal. Other sequelae include loss of strength and self confidence, which can limit mobility and willingness to take part in social activities outside the home. A rise in serious head injuries resulting from elderly who fall has also been noted (Kannus et al. 1999). Not every fall results in injury. Roughly 5% of falls result in serious injury requiring medical attention (CDC 2003; U.S. Census Bureau 2003).

Common sense informs us that one can reduce the number of fall-related injuries in two ways: (a) reduce the number of falls by intervening on the risk factors for falls (for example, Weerdestyn et al. 2006), and (b) when a fall happens, reduce the risk of injury from that fall (for example, DeGoede & Ashton-Miller 2002 & 2003, Groen et al. 2005, Lo 2006). As far as the first approach is concerned, many extrinsic and intrinsic risk factors for falls have been identified (for example, Tinetti et al. 1994) and several types of interventions have been developed to address the most important of these factors. However, the number of falls each year remains high and the probability of ever reducing the number of falls to zero is non-existent. Furthermore, sooner or later everyone falls unintentionally, regardless of their age. So, the second approach leads us to want to find out what people need to know *a priori* and what they need to do during a fall so that they can avoid injury when they do suffer the inevitable fall.

It is known that when a fall results in the greater trochanter directly impacting the ground, then the risk of hip injury is 30 times higher that when the greater trochanter does not strike the ground (Nevitt et al. 1993, Hayes et al. 1993, Schwartz et al. 1998). The underlying message from these studies is that if an elderly person falls, "don't, ever, land on your greater trochanter".

The objective of this study was to estimate whether it is feasible for individuals to twist their pelvis during the ongoing fall in order to avoid landing on their greater trochanter. Do they have the hip external rotator strength that is needed to rotate the hip within the time it takes their pelvis to hit the ground? How do factors like age, gender, body mass, and obesity affect this calculation. Because, actual falls carry a risk for injury, we instead used literature values for muscle strength, our own experimental measurements of hip muscle strength in two individuals, and computer simulations to answer the question.

The technical question we wanted to answer is how long (in msec) it takes a healthy person to volitionally twist their pelvis through a set angle (in order to present the posterolateral part of their thigh/buttocks, rather than the greater trochanter, to the landing surface). In Feldman and Robinovitch (2007) the average axial rotation of the pelvis/hip upon impact from an unexpected lateral fall was 8 degrees in a posterolateral direction. However, from their Figure 2b, Appendix A, we see that an axial rotation angle of 20 degrees would suffice (a) to land on the maxim depth of muscular 'padding' over the bony pelvis, and (b) to land on the aspect of the pelvis that does not include the greater trochanter. In other words, subjects need to axially rotate their pelvis at least 12 degree more than normal and ideally 22 degrees more than normal. We also chose to find out how long it takes to twist the pelvis through more than enough rotational angle, i.e., 30 degrees, given unilateral stance and full foot-floor frictional contact conditions. Finally, we need to find out how much this latency is affected by advancing age, increasing body mass, and decreasing hip muscle strength, and obesity.

A rough calculation for this time can be made by knowing the reaction time for the onset of muscle activity (~60 - 166 msec) (Ashton-Miller, Thelen 1996) and then adding the time required for muscle to develop enough contractile force and torque to rotate the hip externally 30 degrees, as well as counter rotate what was the stance leg in an internal hip rotation direction through 30 degrees in the opposite direction, thereby rotating the greater trochanter away from the impact site. This second rotation would require the hips to rotate 3° in the opposite direction relative to the first turn, and the leg to rotate 30°. If this time is less than the mean 626 ms (SD =40) (Feldman, et al. 2007) showed that it takes to fall sideways, then this calculation provides the theoretical basis for expecting that there is time for both young and elderly to present the "correct" posterolateral part of the pelvis (i.e., buttock) for impact with the ground in a sideways fall.

2. Materials and Methods

Two male subjects- A: 21 years old, 180 cm tall, and 72 kg, and B: 60 years old, 190 cm tall, and 84 kg, participated in the study. Each subject wore a belt around the top portion of their iliac crest (waist). A set of three infrared light-emitting diode markers was attached to the belt. Using an Optotrak Cetrus system each marker location could be measured in 3-D space and the change in hip angle during the course of a volitional axial turn of the pelvis could be calculated. The experiment began with the subject having one foot planted on top of an AMTI OR-6 force plate and the other foot lifted off the ground behind the individual. The subject would then twist their pelvis as quickly and as far as possible three times in either a clockwise or counterclockwise direction of rotation, while keeping their planted foot stationary. The peak torques, degree of turns, and time to turn was then calculated and descriptive statistics calculated.

The isometric torque values were recorded by having one foot planted on the force plate while the subject held a stationary ladder in front of them. The subject would then apply a torque to their foot while keeping their hips and foot stationary.

Adams

A model was created in Adams to simulate the motion of the hip, thigh, shank, and foot (Appendix K). One model, "fixed", was created which had the foot and leg had fixed to the ground which only allowed rotational motion of the hips via a torque source at the "hip". The angle of turn between the pelvis and ground, and the hip torque input was computed. For simplicity, a second model, "free", was created which represents the second part of the fall - when the foot has lost contact with the ground and a counter torque reaction is required at the hip. This counter torque moves the greater trochanter "away" from the impact area so that the posterior buttock becomes exposed to the impact. The values of inertia and dimensional values used for the hip, thigh, and shank were taken from Anthropometric Source Book (NASA, 1978).

The moment of inertia for the whole body was based on the results of David Carrier's article, 'Influence of Increased Rotational Inertia on the Turning Performance of Humans', for varying whole-body masses (Appendix B). These were extrapolated from the range of body masses of the subjects were used to the average masses of males and females for the young adults (age 20-29 years), heaviest age bracket, mid age, (age 40-49 years), and the old (age 60-74 years) (U.S. Department of Health and Human Services). The decrease in external hip muscle torque between 20 and 70 years was scaled from the maximum voluntary ankle dorsiflexor strength data reported by Darryl G. Thelen et al. in their article 'Effects of Age on Rapid Ankle Torque Development", Table 2 (Appendix D, E). We made the assumption that the hip internal and external hip rotator muscles have identical maximum torque-time characteristics to the ankle dorsiflexors. We made this assumption because we could find no data in the literature on age and gender effects on hip internal and external rotator muscle strengths, and because the volume of muscle is approximately similar.

3. Results

Sample plots of the experimental results showing the angle of turn, torque, and angular velocity against time can be seen in Appendices F-J. The "best" hip rotator strength test results came from the trials which involved turning clockwise for both the right and left foot planted- which correlated to the internal and external rotation muscles respectively. The peak torque values were taken at the second peak, at which point the angle had the largest magnitude. The change in time for the angle was taken as the time for the angle to reach 90% of its maximum value from 10% of its baseline value at rest. Table 1 below, shows the averaged results of these trials with precision error.

Table 1: Maximum volitional internal and external hip rotator muscle strength and turn test results

	Interal rotation		External rotation	
Subject:	**A**	**B**	**A**	**B**
Peak angle of turn (degrees)	29.11 ±3.27	29.44 ±1.39	30.33 ±6.42	23.10 ±3.45
Max angular Velocity (deg./sec)	131.9 ±26.8	116.7 ±23.1	121.1 ±26.3	83.3 ±18.0
Peak torque (Nm)	31.82 ±9.73	19.60 ±4.20	27.14 ±5.54	19.18 ±1.57
Δtime for torque zero to peak (sec.)	0.195 ±.096	0.162 ±0.033	0.284 ±0.030	0.340 ±0.278
Δtime for angle (sec)	0.315 ±.266	0.264 ±0.077	0.290 ±0.105	0.313 ±0.066

These results were input into the Adams simulation along with the extrapolated values from the methods section. The results of these trials can be seen in Appendix N. All trials that did not complete the second rotation of turning the leg 30° could also not complete the internal hip rotation of 3° either. It was found that for the average inertia, 1.12 kgm^2, if the time was 100 ms for the free leg, subject A at 50% of its strength and subject B did not complete the required angle of 30°, as seen in Figure 1 below. For the fixed leg simulation, only subject A at 50% of his strength was under the 30° for 400 ms. When running the simulation with subject A and B's experimentally determined torque and extrapolated inertias respectively, Figures 2 and 3 below, subject A met all requirements while subject B did not meet the internal goal at 100 ms and external requirement at 350 ms. When looking at the results for the extrapolated inertias and torques based on the averaged weights and loss of muscle strength for the young, middle aged, and old males and females, no females were able to make the required 30° external rotation at 100 ms while all males succeeded. For the internal rotation, all males could meet the requirements at 350 ms and above, while middle-aged females could not meet it at 350 ms, and old females could not meet it at 400 ms. In the extreme case for males and females 45 years old and above, who are of the upper 95 percentile of their weight bracket, none could meet the internal rotation requirement at 100 ms as seen in Figure 6. As for the external rotation, no male could meet the angle requirement by 400 ms, middle aged female by 450 ms, and old female by 500 ms.

Figure 1: Results with average inertia, 1.12 kgm^2

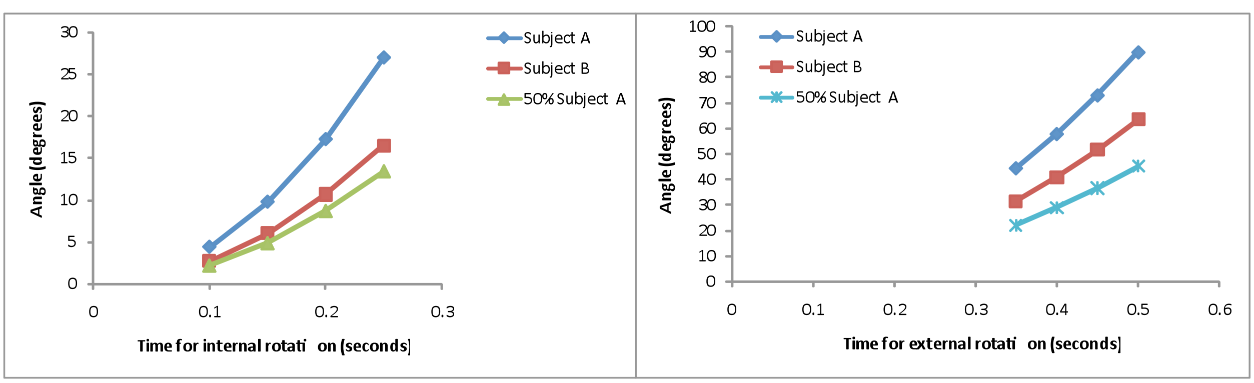


Figure 2: Results with subject A inertia, 1.04 kgm^2

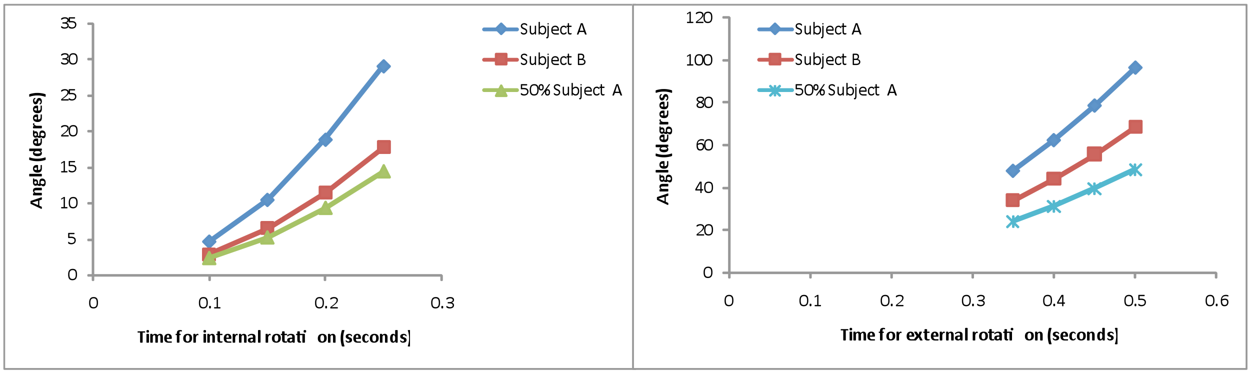


Figure 3: Results with subject B inertia, 1.327 kgm^2

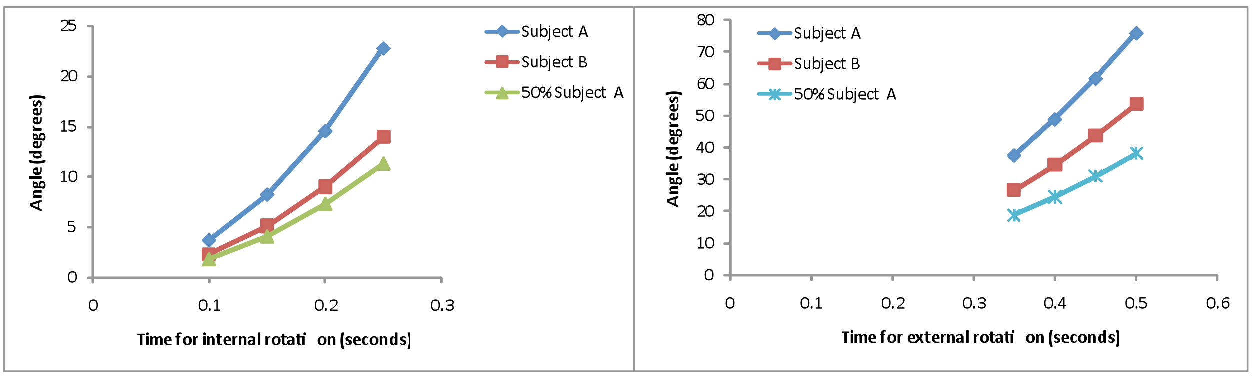


Figure 4: Results for extrapolated strength based on age for females

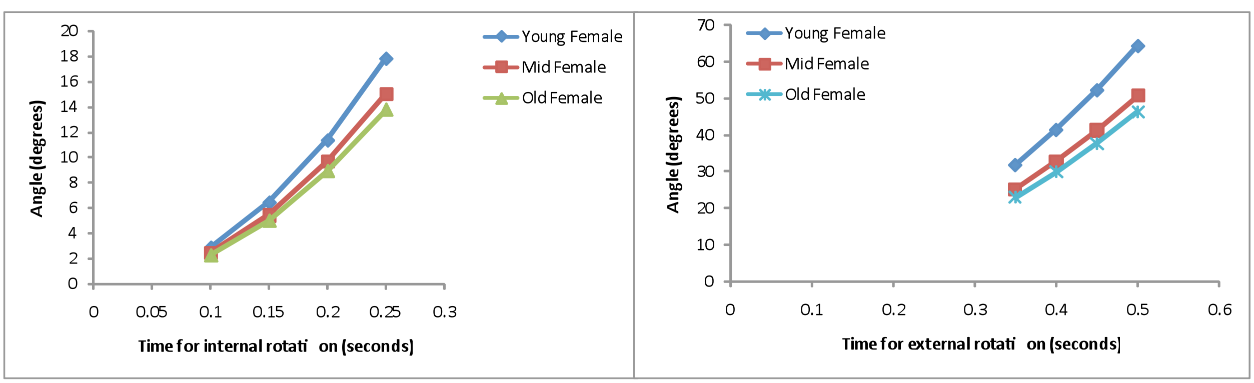


Figure 5: Results for extrapolated strength based on age for males

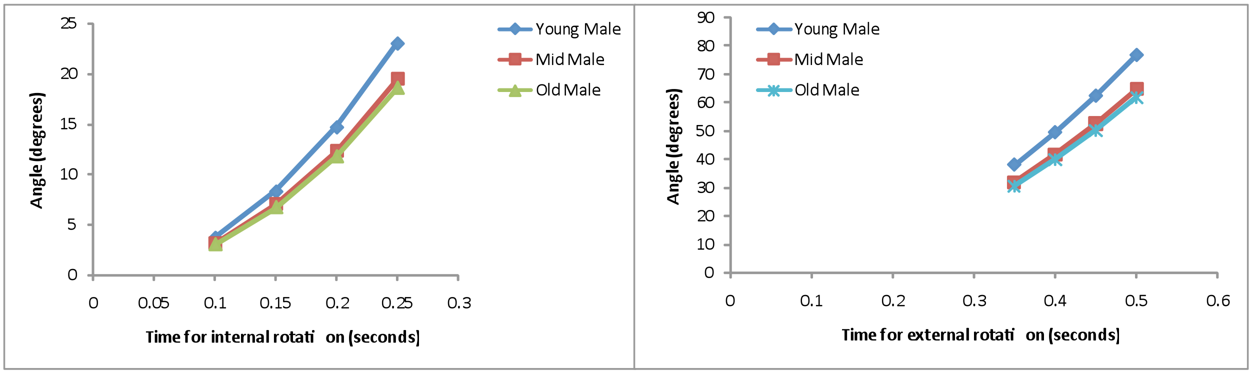
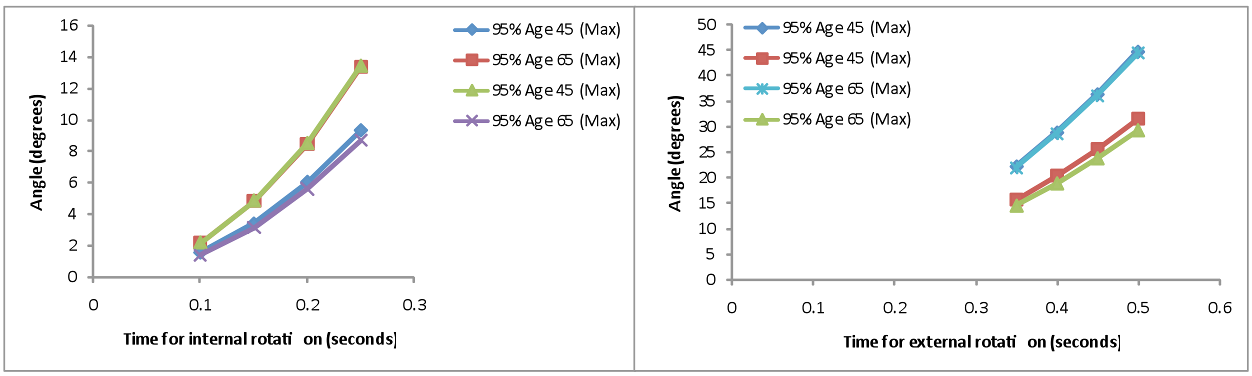


Figure 6: Results for upper 95 percentile weight



The minimum required torques to complete a 3° turn for the internal rotation of the hip and 30° turn for the external rotation for different times can be seen in Table 2, below. The inertia values were extrapolated based on the average weight for males and females of ages 45 (mid) and 65 (old). In Table 3 the maximum allowable inertia and extrapolated mass was calculated for set average maximal torque values to complete the same turn angles. The average torque values came from the extrapolated average strength loss based on age and gender found by Thelen et al.

Table 2: Minimum torques to reach set angle of turn for average weighted people

			Free (RCW)		Fixed (LCW)		
		time (sec)	0.1	0.15	0.35	0.4	0.45
	Avg. Mass (kg)	Inertia (kgm^2)	Min Torque (Nm)				
Mid Female	76.9	1.1566	22.80	10.20	18.75	14.50	11.45
Old Female	74.9	1.1086	22.00	10.00	18.04	13.92	11.00
Mid Male	89.1	1.4494	28.00	13.00	23.60	18.10	14.40
Old Male	87.1	1.4014	27.20	12.15	22.80	17.56	13.95
	Desired angle of turn (degree)		3	3	30	30	30

Table 3: Maximum Inertia values to reach set angle of turn for average strength people

	Free (RCW)					Fixed (LCW)						
	time (sec)	0.1		0.15			0.35		0.4		0.45	
	Avg. Torque (Nm)	I (kgm^2)	Mass (kg)	I (kgm^2)	Mass (kg)	Avg. Torque (Nm)	I (kgm^2)	Mass (kg)	I (kgm^2)	Mass (kg)	I (kgm^2)	Mass (k
Mid Female	18.444	0.96	68.71	2.1	116.21	15.73888	0.97	69.13	1.26	81.21	1.58	94.
Old Female	16.218	0.85	64.13	1.87	106.63	13.83936	0.85	64.13	1.109	74.92	1.39	86.
Mid Male	29.574	1.52	92.04	3.4	170.38	25.23648	1.55	93.29	2.02			
Old Male	27.348	1.4	87.04	3.15	159.96	23.33696	1.43	88.29	1.86			

4. Discussion

Based on the results, one can conclude that an individual's inertia and strength has a marked effect on their ability to rotate their pelvis and protect their hip from impact in a fall. Assuming that an angle of 30° is needed for the initial external rotation, 3° for the second internal rotation of the hip, 30° for the second rotation of the leg, a response time of 100 ms, and a time to fall of around 626 ms, those most at risk of not being able to exercise the proper fall technique would be elderly females, while the middle aged female would also be at a risk. This is due to the lower available strength in women in comparison to men. For the extreme case of having a weight in the upper 95% percentile, all are at risk of not being able to complete a fall with the correct technique. However due to increasing obesity in the population, one would have to look further into a scan of the pelvis region to see if an angle of 30° is required, or if there is enough excess tissue to supply enough cushion for the greater trochanter in a fall if one rotates the pelvis less.

The second turn completed by using the internal rotator muscles, was completed by all tests in less than 150 ms and therefore is not a bottleneck for the fall process. This is due to the leg having significantly smaller rotational inertia than the torso. The initial phase of external pelvic rotation holds the most significance. Based on the experimental results for maximal angular pelvic velocity (approximately 100 degrees/sec) and the knowledge that the normalized torque occurs at the same time no matter an individual's age or strength (Thelen), all turns seem feasible to complete in the required time. However, not all turns in the experiment were completed past

30°**.** This could be a flexibility issue which is a separate issue. Women would be expected to be more flexible than men, so lack of flexibility may not be a problem for them.

Limitations of the study are the assumption that maximum voluntary hip external and internal rotator muscle torques are similar to maximum voluntary ankle dorsiflexor muscle torques. In addition, our estimates of single leg rotational inertia were only approximate and need to be improved. The experimental hip torque data was measured with one foot planted on the ground while the subject anticipated the turn and started from a balanced stance. In a real life situation a loss/lack of friction under an individual's feet would cause an imbalance by surprise. In addition, when looking at the graphs for the experimental torque, there was often a high torque value in the opposite direction before the maximum angle of turn. This suggests a preparatory muscle tension in the experimental trials which would not be available in a surprise fall. This makes the experimental values an upper limit and with a short reaction time. This can also be seen when comparing the isometric torque values, Appendix O, with the experimental ones- which are higher. Finally, we measured hip isometric strength and rotational performance data on only two males. More data are needed on men as well as women of different ages.

5. Conclusions

1) These calculations suggest that all healthy individuals should be capable of axially rotating the pelvis through an angle of 20° in order to avoid presenting the greater trochanter to the ground in a fall.

2) If a full 30° turn angle is required to be completed, then older individuals, and particularly females and obese individuals, over the ages of 45 years may not have sufficient strength to achieve the avoidance maneuver.

3) To avoid injury it is important to retain hip internal and external rotation flexibility, and for those at risk for hip fractures to increase their hip rotator muscle strength.

4) Further hip muscle strength and performance testing should be completed in order to obtain a better representation of the capacities of both genders of different weights and ages.

5) Further research should involve actual fall tests to see if the required neuromuscular coordination for the greater trochanter impact avoidance maneuver is in fact available during an actual fall to the side.

Acknowledgements

I would like to thank Dr. James Ashton-Miller for all his help, guidance, and patience with me on this project. I would also like to thank Hogene Kim for all his help in setting up the labs and teaching me Matlab as well as Yunju Lee for her help with setting up the Adams simulations.

References

Alexander BH, Rivara FP, Wolf ME. The cost and frequency of hospitalization for fall-related injuries in older adults. *Am J Public Health* 82(7):1020-3, 1992.

Centers for Disease Control and Prevention, Surveillance for Injuries and Violence Among Older Adults. Retrieved December 17, 2007, from http://cdc.gov/MMWR/preview/mmwrhtml/ss4808a3.htm, 1999 Dec 17.

Centers for Disease Control and Prevention. 17 Dec. 2007 <http://www.cdc.gov/ncipc/duip/preventadultfalls.htm>, 2003.

Feldman F, Robinovitch SN. Reducing hip fracture risk during sideways falls: Evidence in young adults of the protective effects of impact to the hands and stepping. *J Biomech* 40: 2612–2618, 2007.

Groen B., Weerdesteyn .V, Duysens J.. Martial arts fall techniques decrease the impact forces at the hip during sideways falling. *J Biomech*, 40(2):458-462, 2007.

Groen B., Weerdesteyn .V, Duysens J. The relation between hip impact velocity and hip impact force differs between sideways fall techniques. *J Electromyog Kines,* 2007.
Hayes WC, Piazza SJ and Zysset PK. Biomechanics of fracture risk prediction of the hip and spine by quantitative computed tomography. *Radiol Clin N Am* 29: 1-18, 1991.

Hayes WC, Myers ER and Norris JN et al. Impact near the hip dominates fracture risk in elderly nursing home residents who fall. *Calcif Tissue Int* 52:192-198, 1993.

Hayes WC and Myers ER, et al. Etiology and prevention of age-related hip fractures. *Bone* 18(1 Suppl): 77S-86S, 1996.

Hausdorff JM, Rios DA, Edelber HK. Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Arch Phys Med Rehab* 82(8):1050-6, 2001.

Hornbrook MC, Stevens VJ, Wingfield DJ, Hollis JF, Greenlick MR, Ory MG. Preventing falls among community-dwelling older persons: results from a randomized trial. *The Gerontologist* 34(1):16-23, 1994.

Kannus P., Palvanen M., Niemi S., Parkkari J., Natri A., Vuori I, and Järvinen M. Increasing Number and Incidence of Fall-induced Severe Head Injuries in

Older Adults. *Am J Epid* 149:143-50, 1999.

Kroonenberg A.J. van den, Hayes W., McMahon T. Hip impact velocities and body configurations for voluntary falls from standing height. *J. Biomech* 29(6):807-811, 1996.

Lee D, Walter R, Deban S, Carrier D. Influence of increased rotational inertia on the turning performance of humans. *The Journal of Experimental Biology* 204, 3927-3943, 2001.

Lo, Jia-Hsuan. On minimizing injury risk in forward and lateral falls: effects of muscle strength, movement strategy, and age. Doctoral Dissertation, Department of Mechanical Engineering, University of Michigan, 2006.

Ogden C, Fryar C, Carroll M, Flegal K. Mean body weight, height, and body mass index, United States 1960-2002. U.S. Department of Health and Human Services. 2004 Oct 27.

NASA Reference Publication 1024. Anthropometric Source Book, Volume I: Anthropometry for Designers. Staff of Anthropology Research Project, Webb Assiociates. Yellow Springs, OH 1978.

Robinovitch SN, Brumer R, Maurer J. Effect of the ‘‘squat protective response’’ on impact velocity during backward falls. *J Biomech* 37, 1329–1337, 2004.

Tinetti ME, Baker DI, McAvay G, Claus EB, Garrett P, Gottschalk M, Koch ML, Trainor K, Horwitz RI. A multifactorial intervention to reduce the risk of falling among elderly people living in the community. *NEJM* 331(13):821-7, 1994 Sep 29.

Thelen D, Alexander N, Ashton-Miller J. Effects of Age on Rapid Ankle Torque Development. *The Journals of Gerontology* 51(5): M226, 1996.

U.S. Census Bureau News. 2008 Jan 6 <http://www.census.gov/Press-Release/www/releases/archives/population/001703.html>, 2003 July 1.

Weerdesteyn V, Rijken H, Geurts AC, Smits-Engelsman BC, Mulder T, Duysens J. A five-week exercise program can reduce falls and improve obstacle avoidance in the elderly. *Gerontology.* 52(3):131-41, 2006.

Appendix A: Figure 2 from Robinovitch

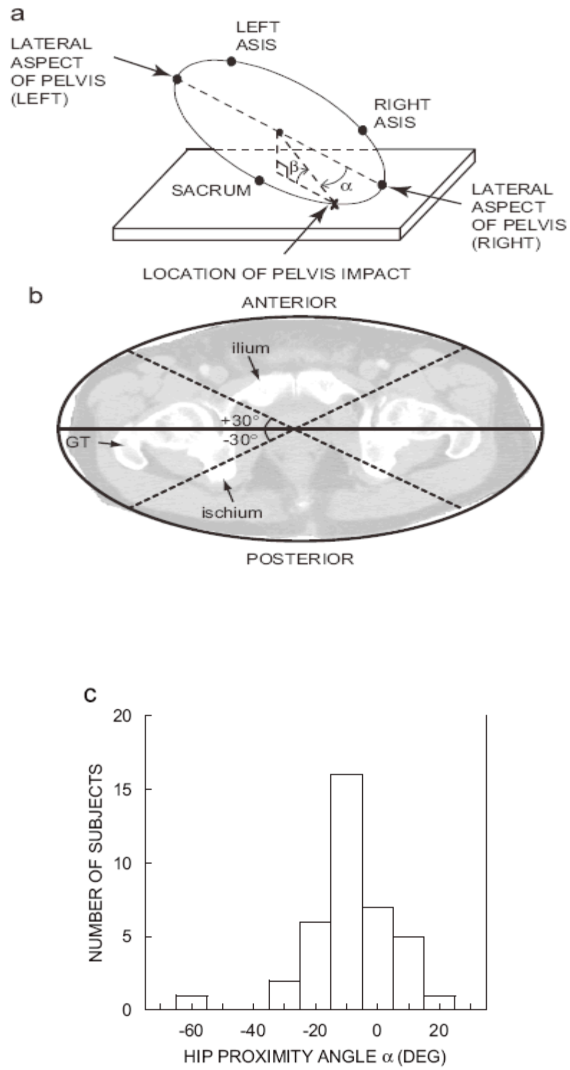


Fig. 2. (a) The hip proximity angle (α) reflected how near the point of impact was to the lateral aspect of the pelvis. To calculate α, we first identified an ellipse whose circumference passed through the sacrum, right ASIS, and left ASIS markers. The lateral aspects of the pelvis were assumed to coincide with the endpoints of the major axis of this ellipse. We then identified the site of pelvis impact as the lowest point on the circumference of this ellipse, at the time of impact. Finally, we defined α as the angle between the site of pelvis impact and the nearest lateral aspect of the pelvis, measured within the plane of the ellipse. (b) Cross-section of the pelvis showing anatomical landmarks. Values of α greater than 30° should result in significant loading of the ilium, and values of $\alpha < -30°$ should load the ischium. (c) Histogram showing the observed distribution of α.

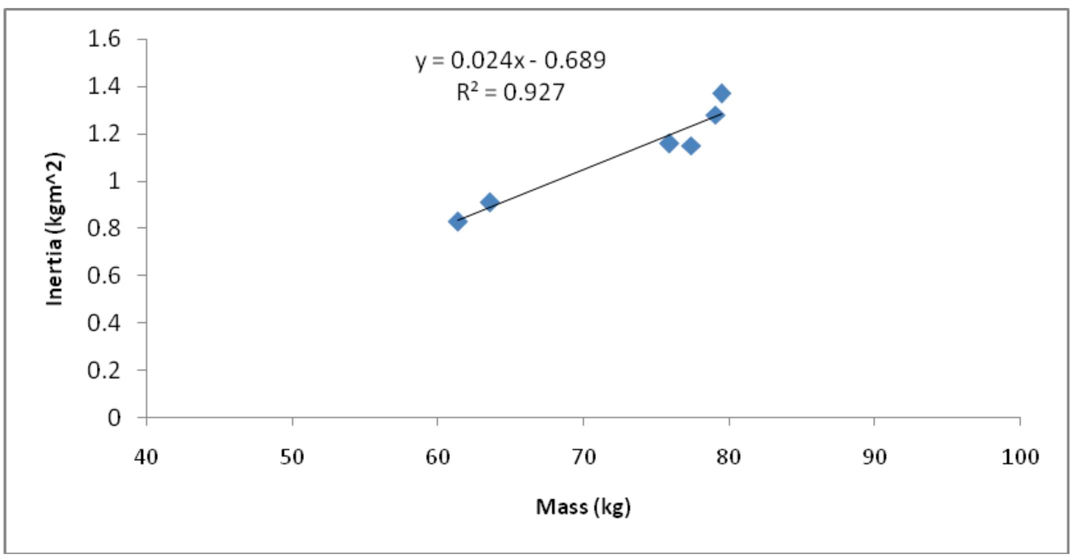
Appendix B: Table 1 from Carrier

Table 1. *Subject mass and rotational inertia during standing and crouching*

		Standing			Crouching	
Subject	Mass (kg)	I_U (kg m^2)	I_W (kg m^2)	I_I (kg m^2)*	I_U (kg m^2)	I_W (kg m^2)
A	79.1	1.28±0.02	1.69±0.03	16.12±0.15 (954%)	2.47±0.16	3.22±0.20
B	75.9	1.16±0.01	1.71±0.04	16.52±0.12 (966%)	2.73±0.17	3.73±0.19
C	63.6	0.91±0.03	1.45±0.04	12.50±0.10 (862%)	1.60±0.18	2.74±0.28
D	79.5	1.37±0.02	1.98±0.01	16.47±0.06 (832%)	2.57±0.13	3.62±0.12
E	61.4	0.83±0.03	1.50±0.02	12.79±0.03 (853%)	1.66±0.10	2.58±0.11
F	77.4	1.15±0.02	1.55±0.04	16.47±0.10 (1062%)	2.35±0.11	3.27±0.23
Mean	72.8	1.12	1.65	15.15 (921%)	2.23	3.19
S.E.M.		0.085	0.079	0.794	0.197	0.188

Means and standard deviations from six trials are given for each subject.
Measurements were unencumbered (I_U), weight-controlled (I_W) or increased inertia (I_I).
*Values in parentheses indicate the increase in rotational inertia as a percentage of weight-controlled values.

Appendix C: Carrier's data extrapolated



Appendix D: Table 2 from Thelen

Table 2. Effect of Age on Maximum Voluntary Strength (MVS) and Maximum Absolute (MRTD) and Normalized (NRTD) Rates of Torque Development in Isometric Tests

	Direction	Young Females	Old Females	*p*-value*	Young Males	Old Males	*p*-value*
MVS (Nm)	DF	28 (4)	22 (3)	< .001	43 (8)	37 (5)	n.s.
	PF	130 (27)	88 (21)	< .001	181 (38)	137 (32)	< .01
MRTD (Nm/sec)	DF	219 (54)	148 (36)	< .001	309 (77)	232 (35)	< .005
	PF	608 (169)	389 (171)	< .005	957 (248)	681 (223)	< .01
NRTD (MVS/sec)†	DF	8.4 (1.0)	7.6 (1.5)	n.s.	7.6 (1.5)	6.5 (0.6)	n.s.
	PF	4.8 (0.8)	4.6 (1.3)	n.s.	5.5 (0.8)	5.3 (1.7)	n.s.

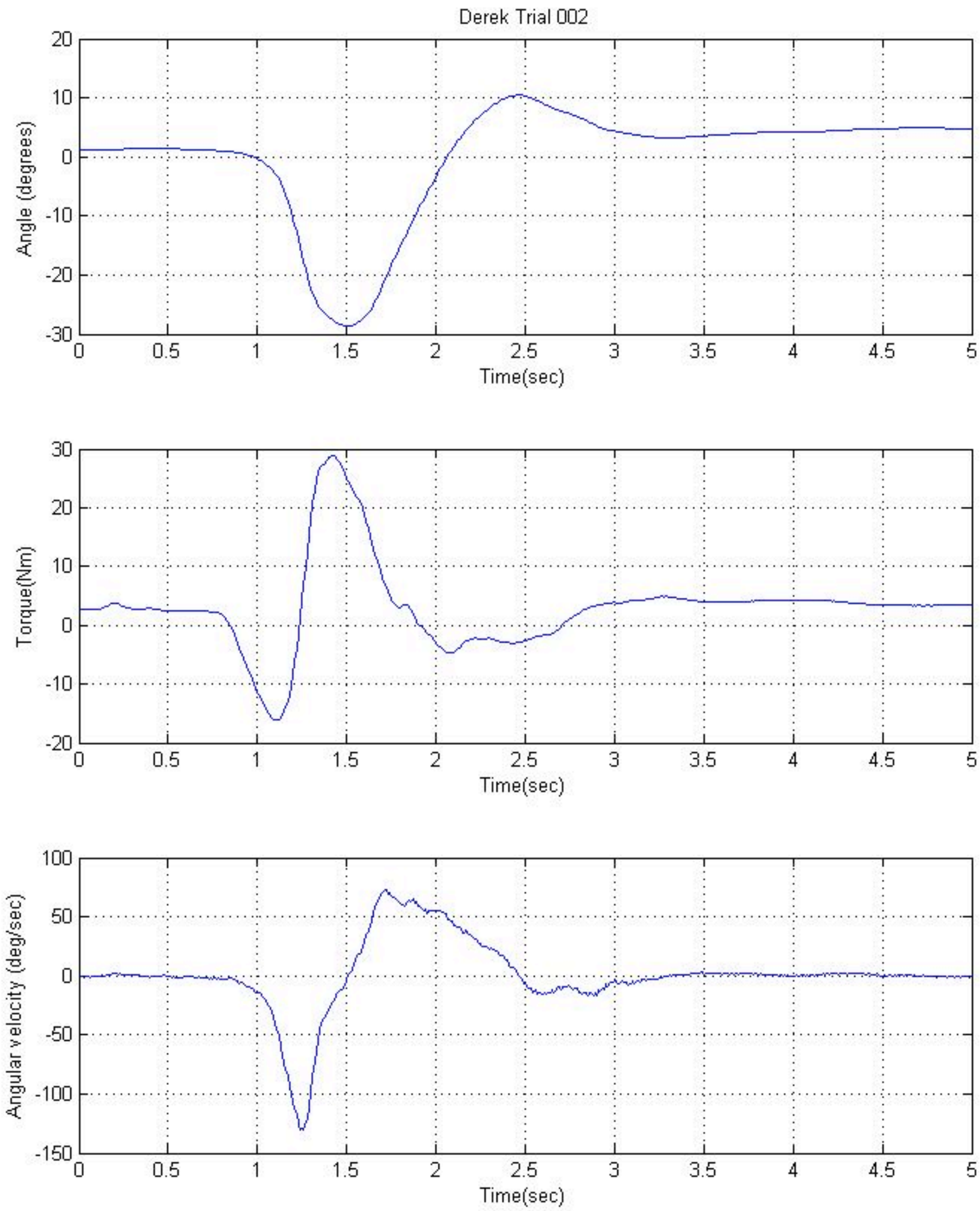
Note. *SD* in parentheses.
*Significant age effects determined by individual *t*-tests.
†This is expressed in multiple of MVS per sec.

Appendix E: Extrapolated data from Thelen

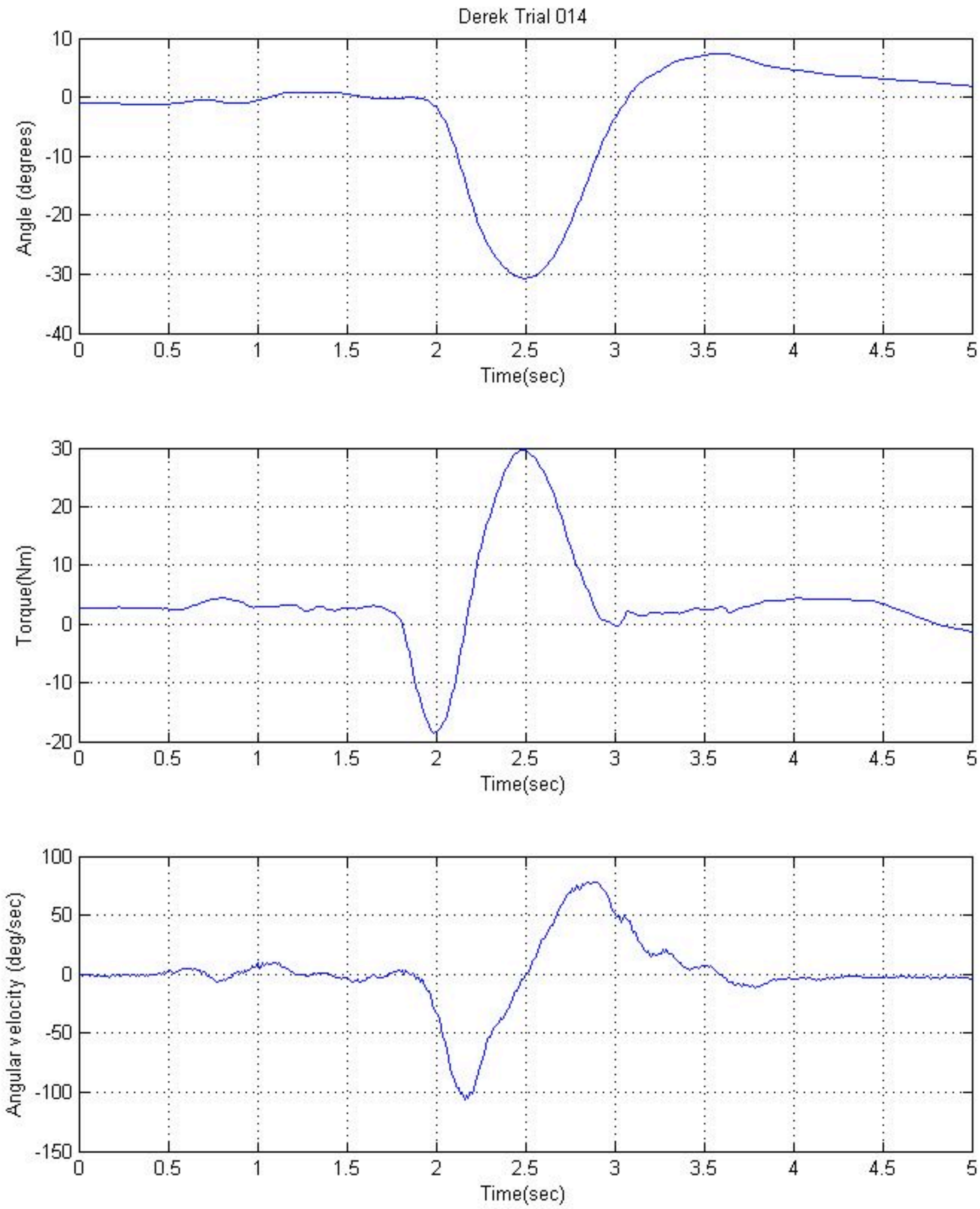
Extrapolated Strength from Thelen

86% Young Male	=	Old Male
65% Young Male	=	Young Female
51% Young Male	=	Old Female
58% Young Male	=	Mid Female
93% Young Male	=	Mid Male

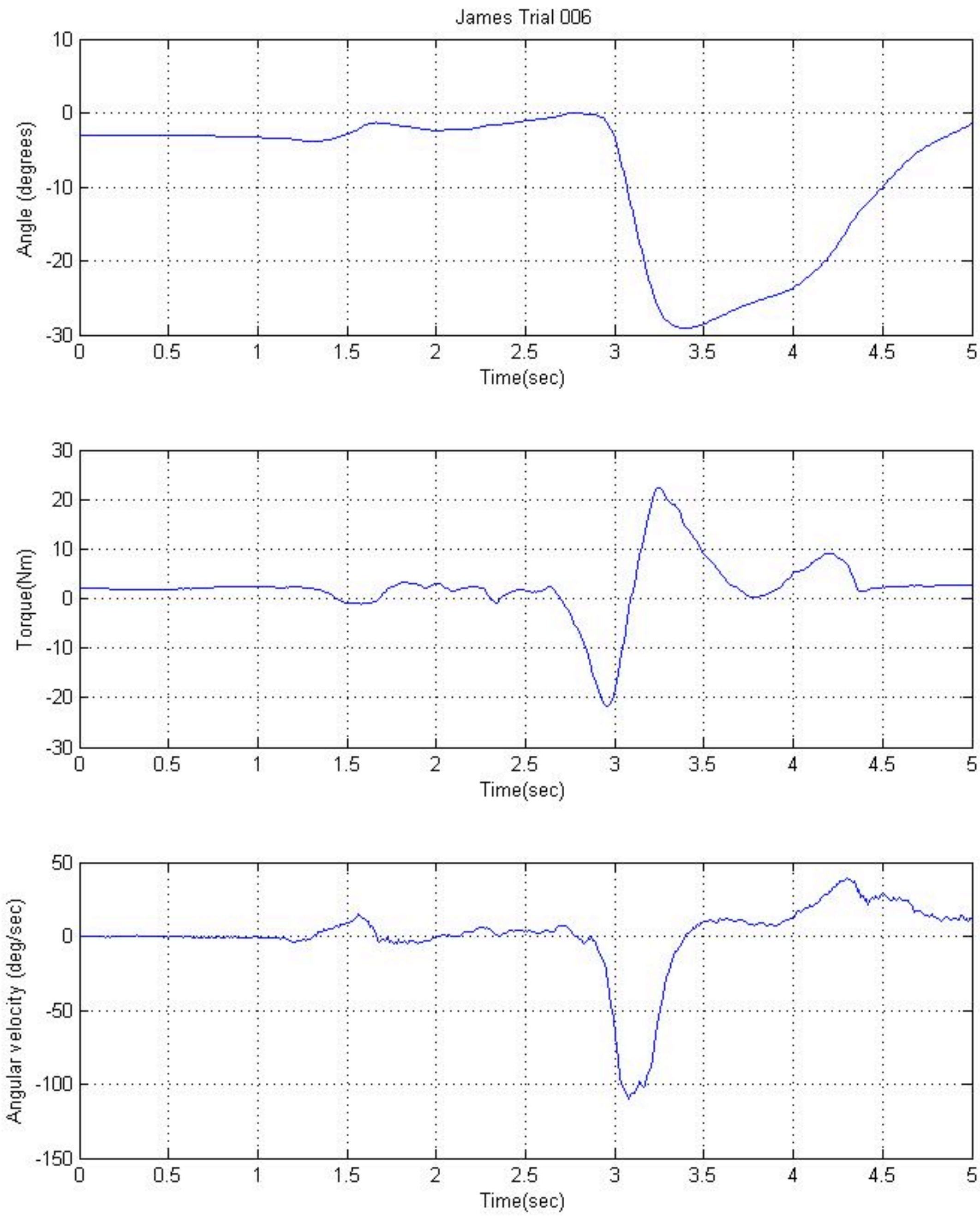
Appendix F: Subject A right foot planted, clockwise turn



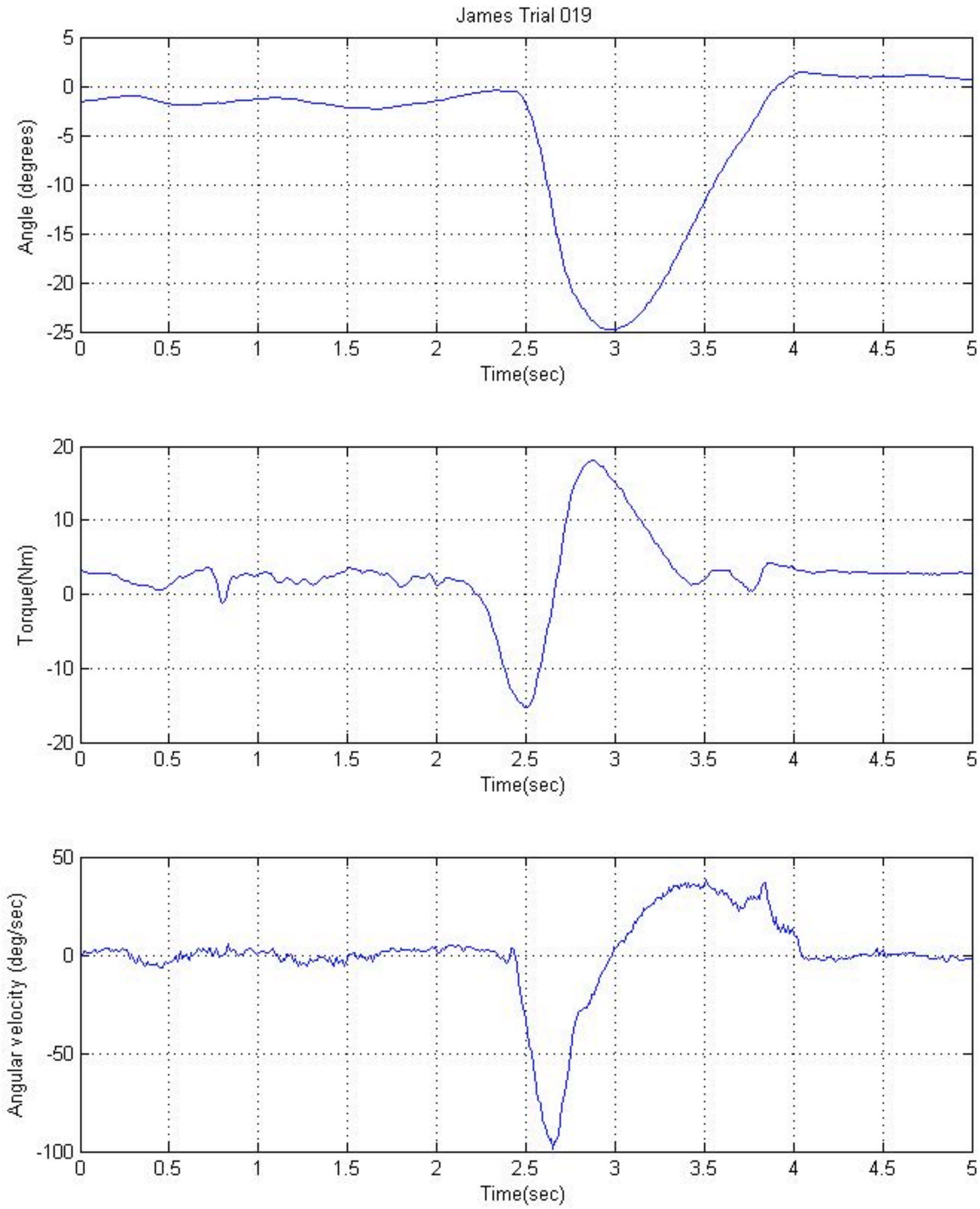
Appendix G: Subject A left foot planted, clockwise turn



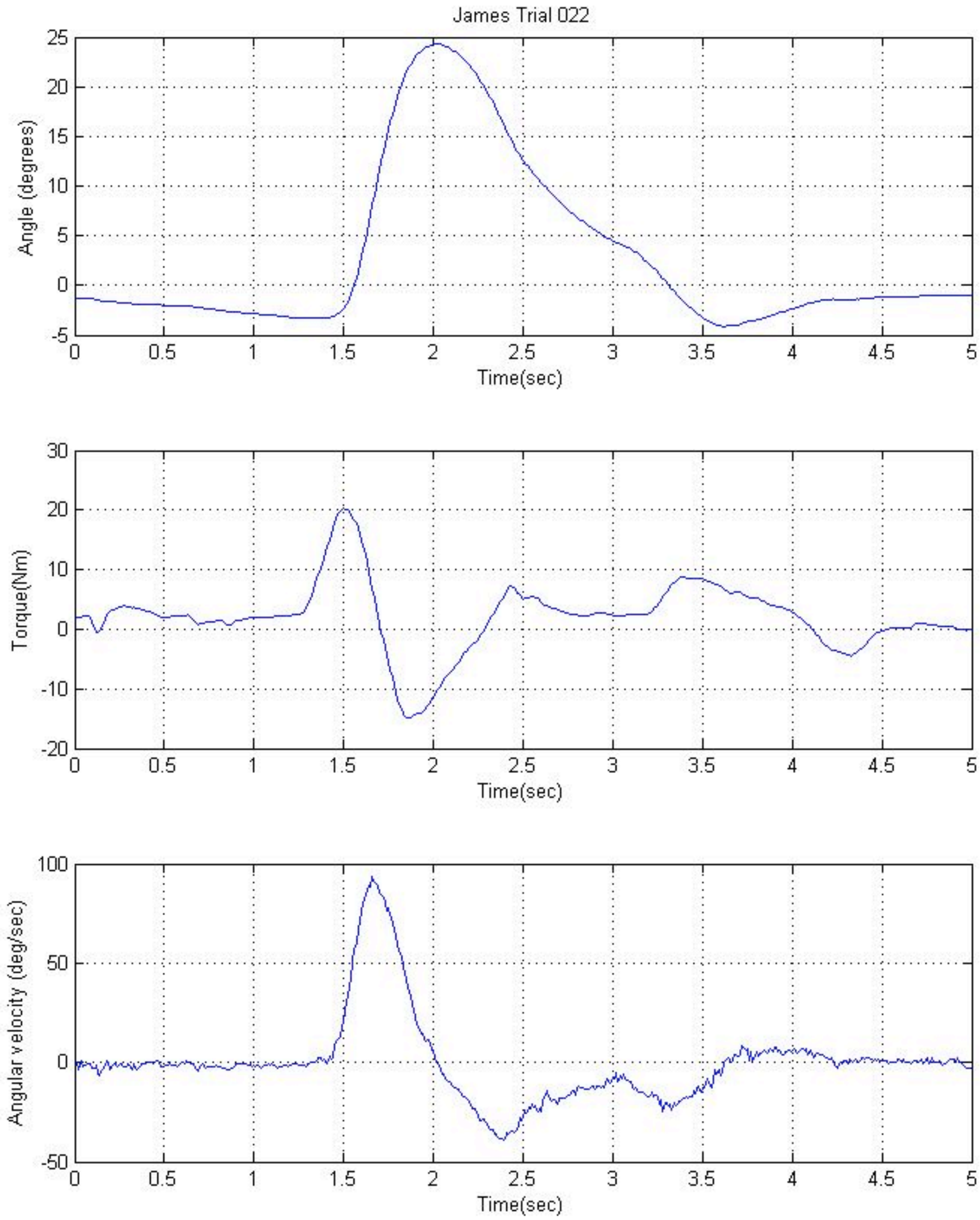
Appendix H: Subject B right foot planted, clockwise turn



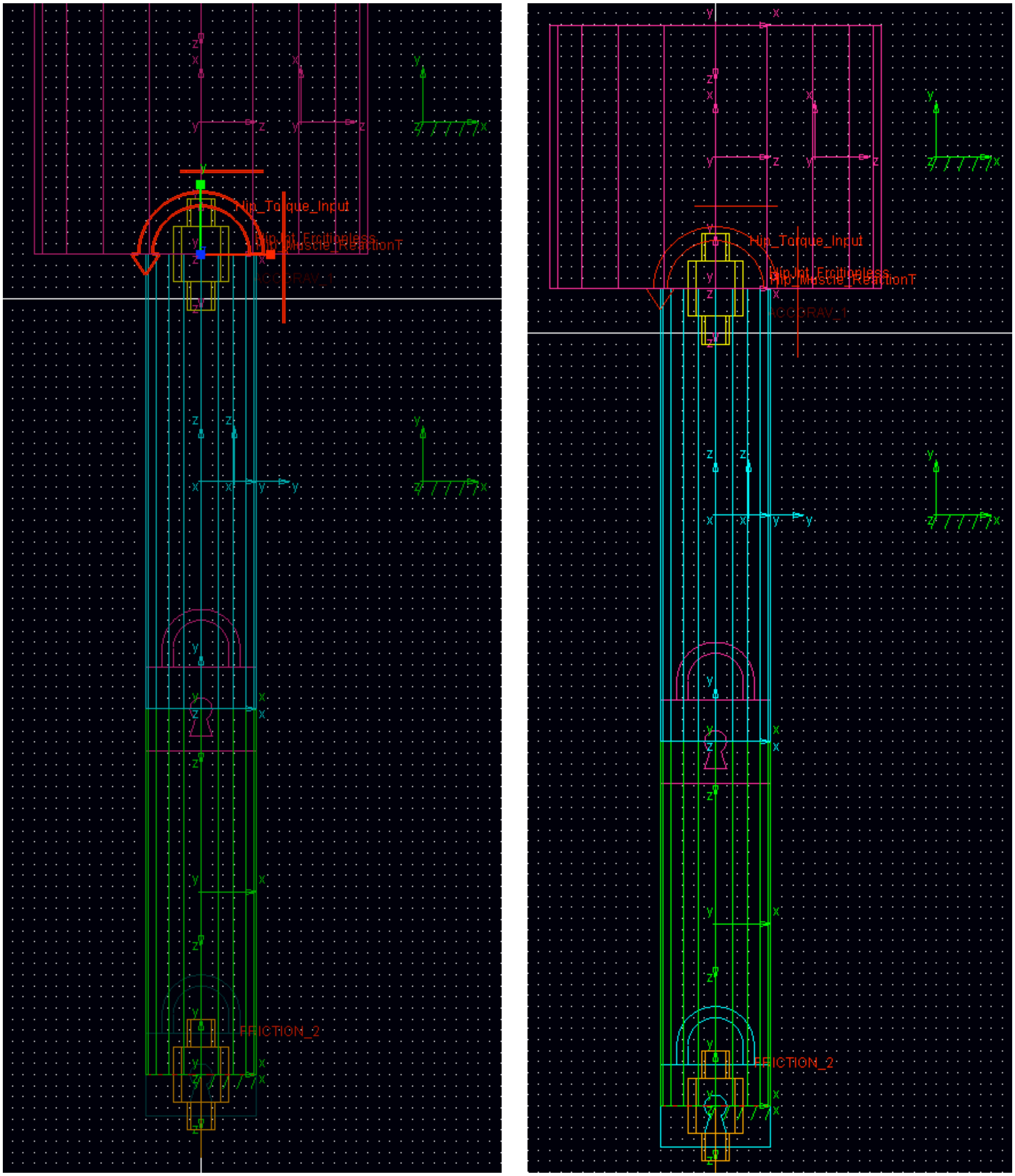
Appendix I: Subject B left foot planted, clockwise turn



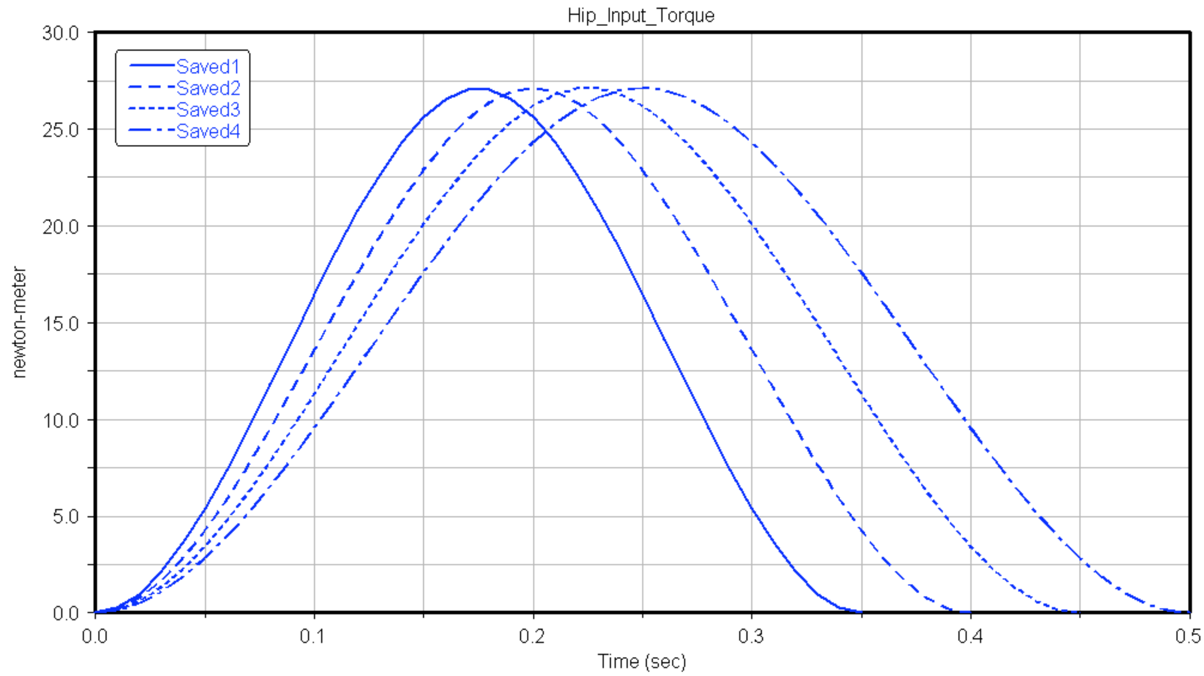
Appendix J: Subject B left foot planted, counterclockwise turn

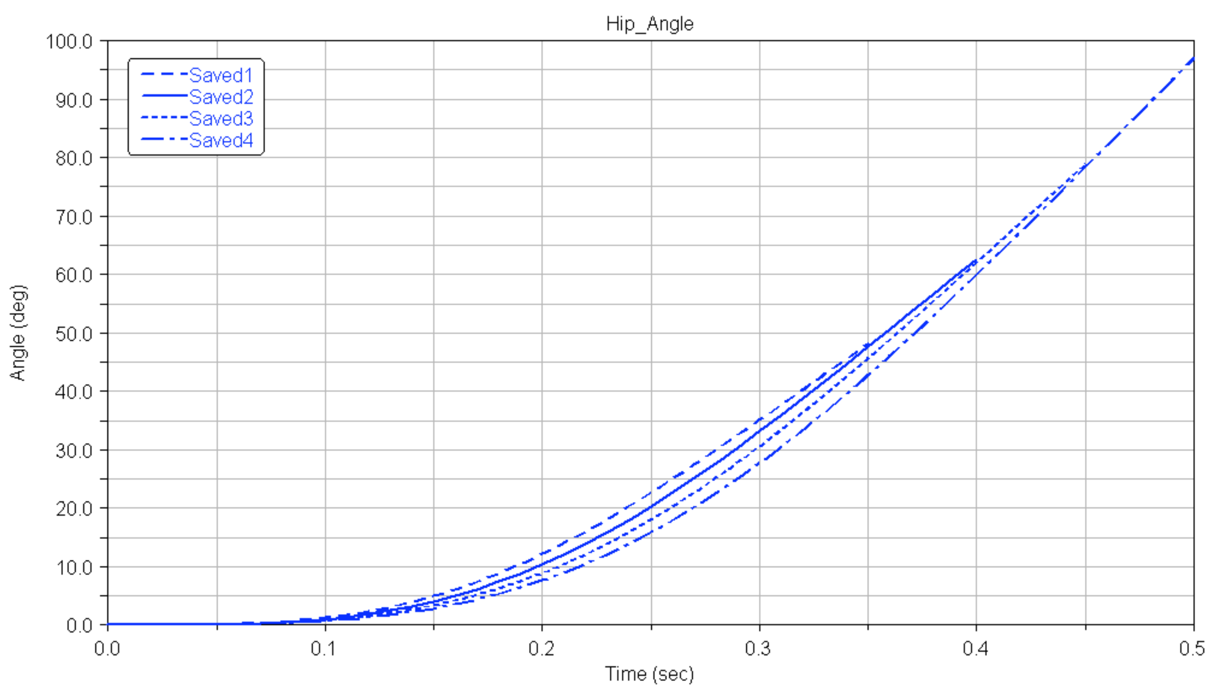


Appendix K: Free (left) and fixed (right) Adams simulation models

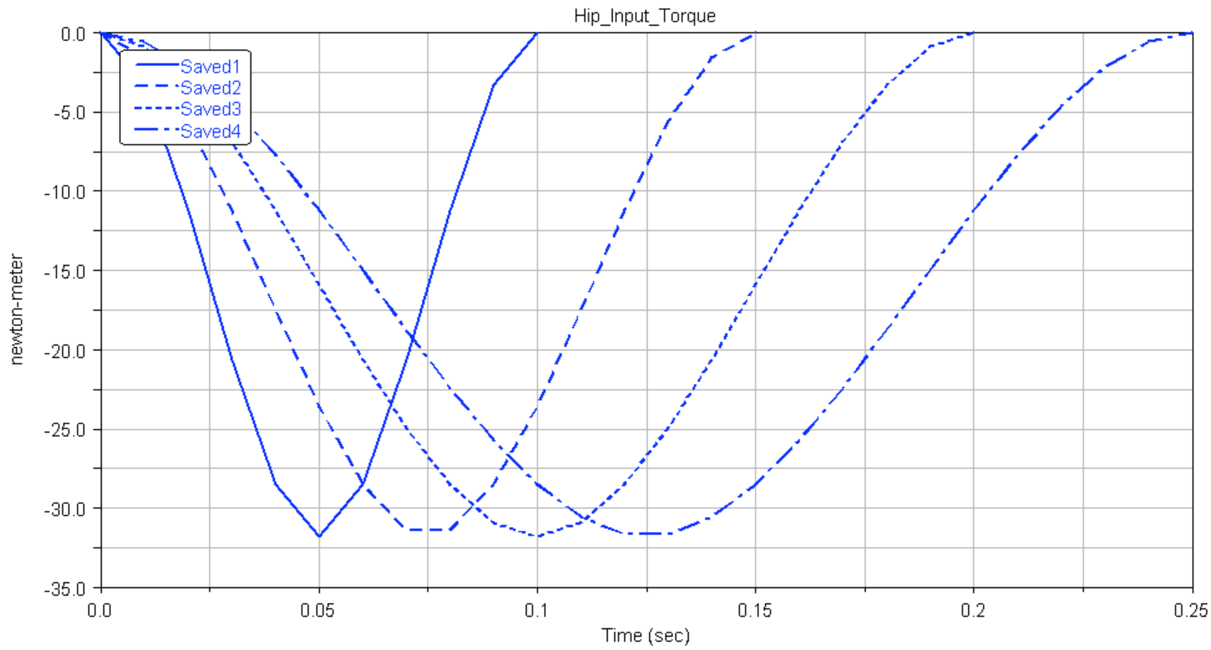


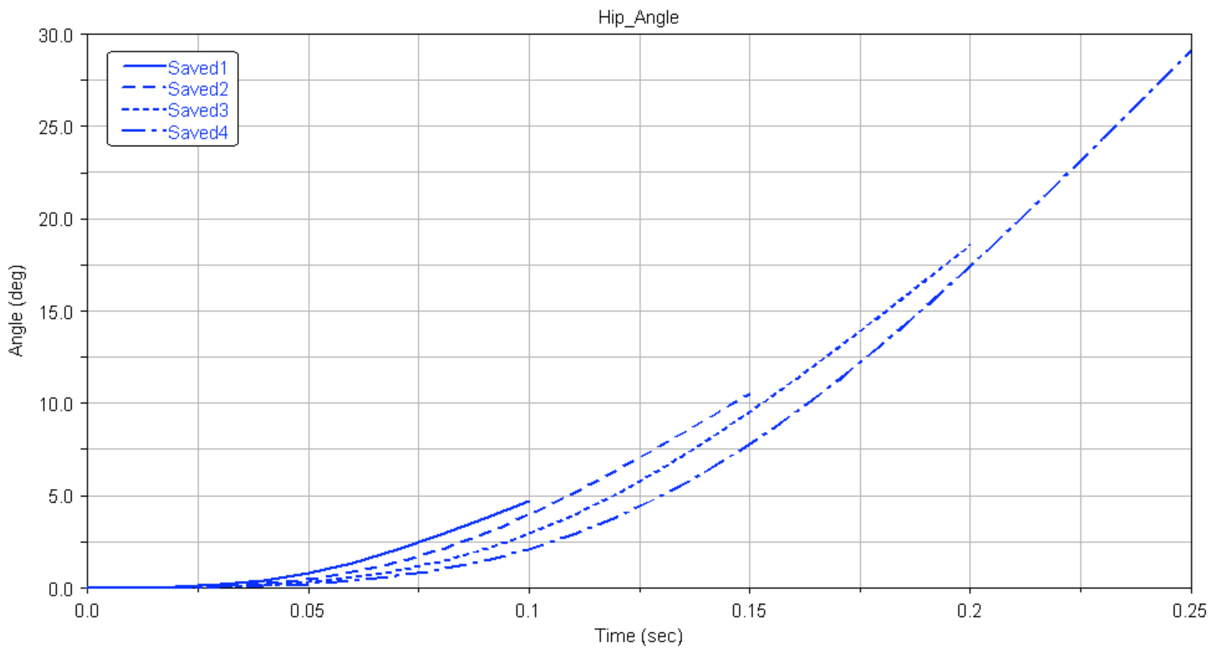
Appendix L: Adams output graph for subject A, fixed, I= 1.04, T= 27.136

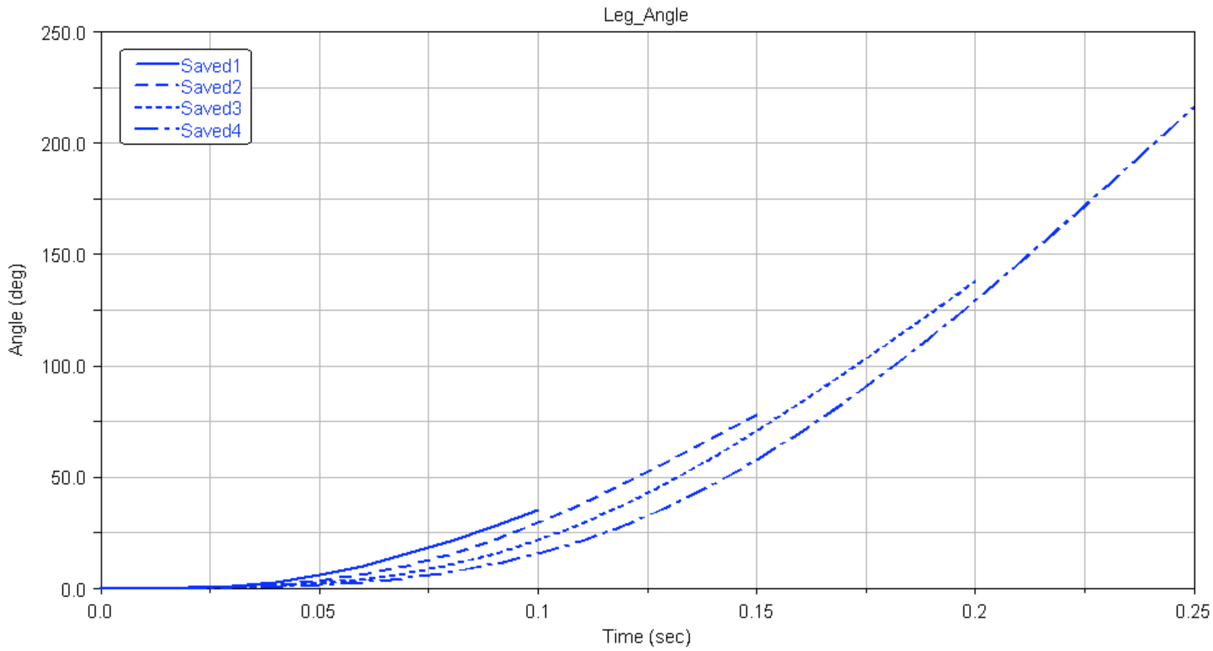




Appendix M: Adams output graphs for subject A, free, I=1.04, T= 31.8



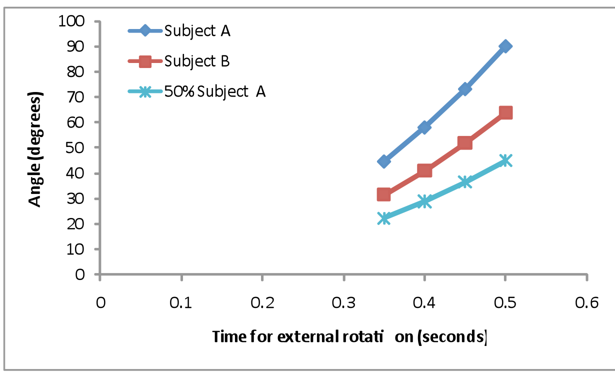


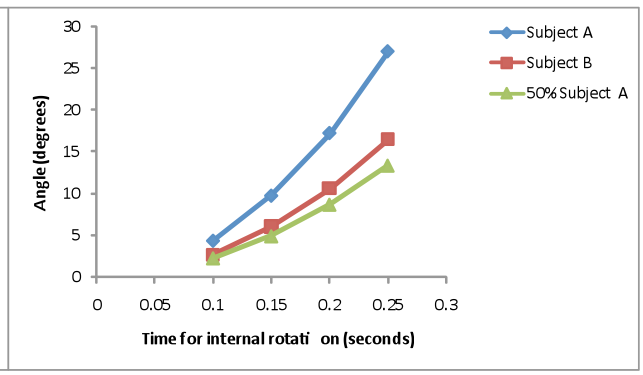


Appendix N: Results of the Adams simulation with varying parameters

Free	RCW	Hip angle (degrees) for ti me (seconds)			
I=1.12	Toque	0.1	0.15	0.2	0.25
Subject A	31.8	4.375	9.759	17.24	27
Subject B	19.6	2.715	6.051	10.65	16.47
50% Subject A	15.9	2.207	4.86	8.665	13.36
		Leg angle (degrees) for ti me (seconds)			
Subject A	31.8	35	78.07		
Subject B	19.6	21.72	48.41	85.22	
50% Subject A	15.9	17.65	38.88	69.32	

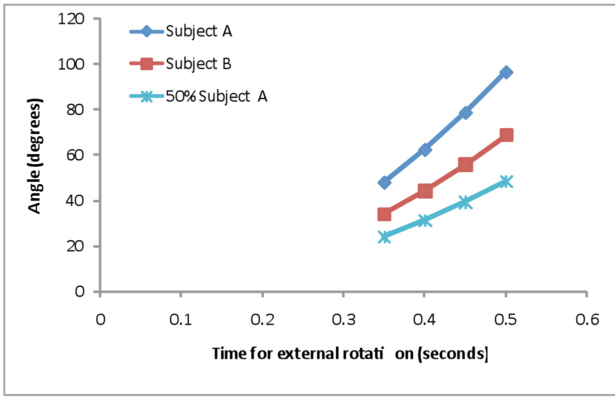
Fixed	LCW	Hip angle (degrees) for ti me (seconds)			
I=1.12	Toque	0.35	0.4	0.45	0.5
Subject A	27.136	44.68	58.07	73.19	90.04
Subject B	19.18	31.58	41.04	51.73	63.64
50% Subject A	13.568	22.34	29.03	36.59	45.02

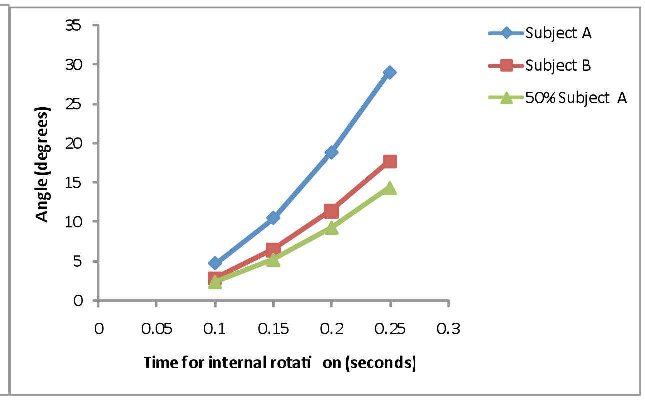




Free	RCW	Hip angle (degrees) for ti me (seconds)			
I=1.04	Toque	0.1	0.15	0.2	0.25
Subject A	31.8	4.712	10.51	18.87	29.08
Subject B	19.6	2.924	6.518	11.47	17.74
50% Subject A	15.9	2.377	5.235	9.334	14.39
		Leg angle (degrees) for ti me (seconds)			
Subject A	31.8	35	78.09		
Subject B	19.6	21.72	48.42	85.24	
50% Subject A	15.9	17.66	38.89	69.34	

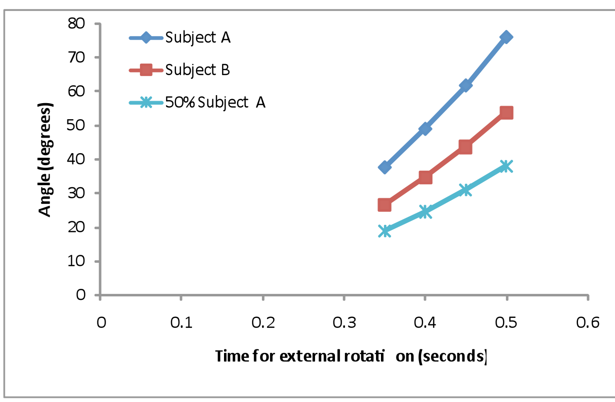
Fixed	LCW	Hip angle (degrees) for ti me (seconds)			
I=1.04	Toque	0.35	0.4	0.45	0.5
Subject A	27.136	48.12	62.54	78.82	96.67
Subject B	19.18	34.01	44.2	55.71	68.53
50% Subject A	13.568	24.06	31.27	39.41	48.48

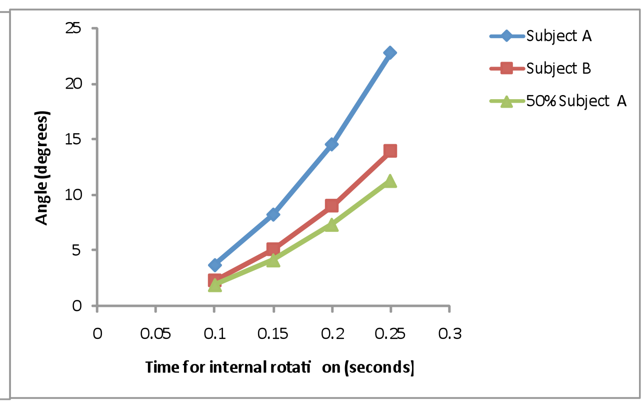




Free	RCW	Hip angle (degrees) for ti me (seconds)			
I=1.327	Toque	0.1	0.15	0.2	0.25
Subject A	31.8	3.691	8.234	14.54	22.77
Subject B	19.6	2.291	5.105	8.985	13.89
50% Subject A	15.9	1.862	4.1	7.309	11.27
		Leg angle (degrees) for ti me (seconds)			
Subject A	31.8	34.99	78.04		
Subject B	19.6	21.71	48.39	85.17	
50% Subject A	15.9	17.65	38.87	69.28	

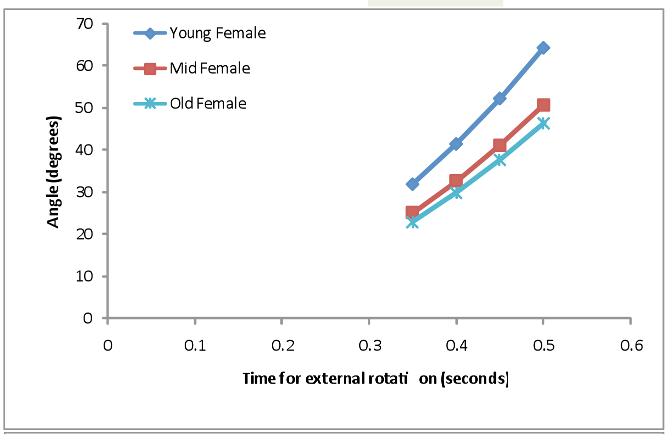
Fixed	LCW	Hip angle (degrees) for ti me (seconds)			
I=1.327	Toque	0.35	0.4	0.45	0.5
Subject A	27.136	37.71	49.01	61.77	75.99
Subject B	19.18	26.66	34.64	43.66	53.71
50% Subject A	13.568	18.86	24.51	30.89	38

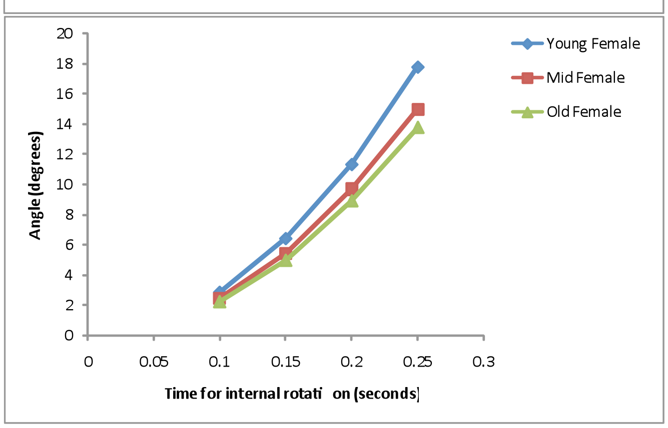




Fixed	LCW			Hip angle (degrees) for time (seconds)			
	Avg. Mass	Inertia	Torque	0.35	0.4	0.45	0.5
Young Female	71.1	1.0174	17.6384	31.97	41.55	52.37	64.43
Mid Female	76.9	1.1566	15.73888	25.18	32.72	41.24	50.73
Old Female	74.9	1.1086	13.83936	23.02	29.92	37.71	46.39
Old M, Mid T	74.9	1.1086	15.73888	26.18	34.03		
Mid M, Old T	76.9	1.1566	13.83936	22.07	28.68	36.15	

Free	RCW			Hip angle (degrees) for time (seconds)			
	Avg. Mass	Inertia	Torque	0.1	0.15	0.2	0.25
Young Female	71.1	1.0174	20.67	2.895	6.454	11.36	17.81
Mid Female	76.9	1.1566	18.444	2.486	5.443	9.719	15
Old Female	74.9	1.1086	16.218	2.274	5.009	8.929	13.77
Old M, Mid T	74.9	1.1086	18.44	2.594	5.679		
Mid M, Old T	76.9	1.1566	16.218	2.18	4.8	8.557	
				Leg angle (degrees) for time (seconds)			
Young Female	71.1	1.0174	20.67	22.91	51.06	89.9	
Mid Female	76.9	1.1566	18.444	20.54	44.97	80.29	
Old Female	74.9	1.1086	16.218	18.01	39.66	70.71	



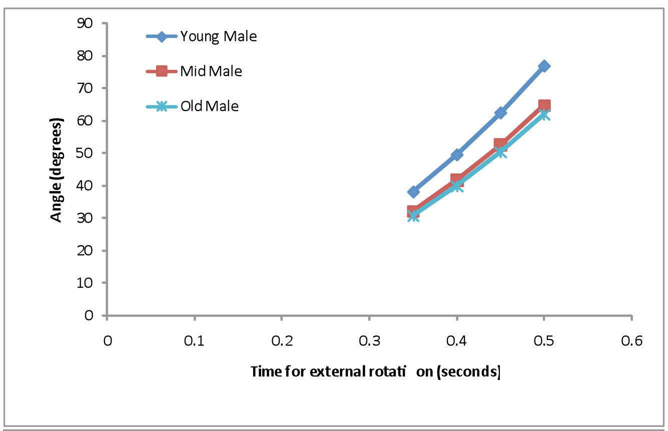


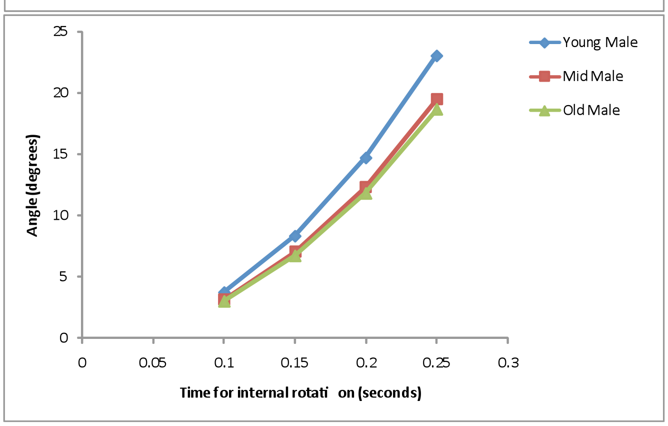
26

Fixed	LCW			Hip angle (degrees) for time (seconds)			
	Avg. Mass	Inertia	Torque	0.35	0.4	0.45	0.5
Young Male	83.4	1.3126	27.136	38.13	49.55	62.45	76.83
Mid Male	89.1	1.4494	25.23648	32.11	41.74	52.6	64.71
Old Male	87.1	1.4014	23.33696	30.71	39.91	50.3	61.88
Old M, Mid T	87.1	1.4014	25.23648	33.21	43.17		
Mid M, Old T	89.1	1.4494	23.33696	29.71	38.61		

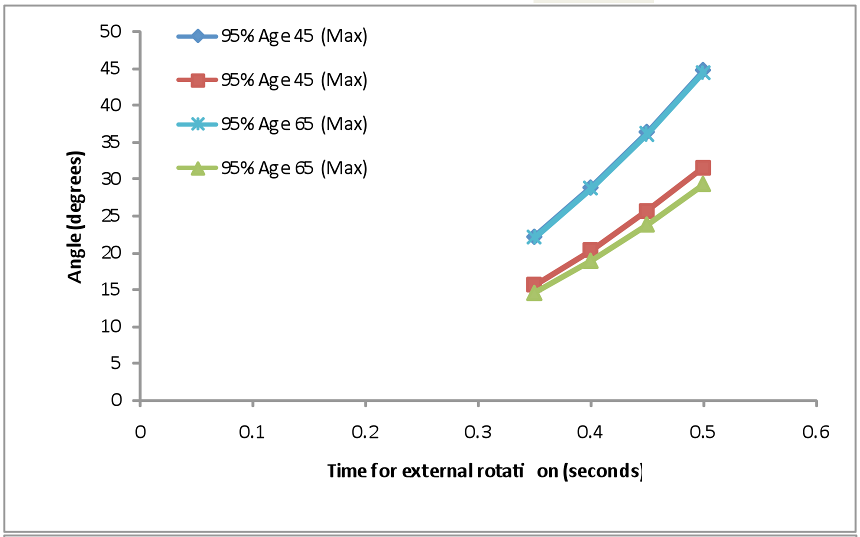
Free	RCW			Hip angle (degrees) for time (seconds)			
	Avg. Mass	Inertia	Torque	0.1	0.15	0.2	0.25
Young Male	83.4	1.3126	31.8	3.732	8.324	14.7	23.02
Mid Male	89.1	1.4494	29.574	3.143	7.014	12.32	19.45
Old Male	87.1	1.4014	27.348	3.022	6.715	11.78	18.6
Old M, Mid T	87.1	1.4014	29.574	3.25	7.255		
Mid M, Old T	89.1	1.4494	27.348	2.922	6.492		

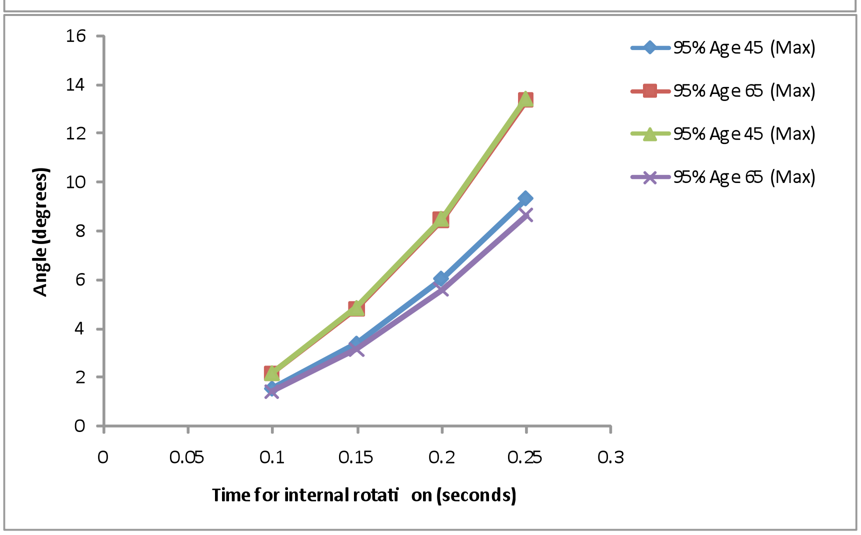
				Leg angle (degrees) for time (seconds)		
Young Male	83.4	1.3126	31.8	34.99	78.04	137.8
Mid Male	89.1	1.4494	29.574	32.54	72.61	127.5
Old Male	87.1	1.4014	27.348	30.25	67.22	117.9





	Fixed	LCW			Hip angle (degrees) for time (seconds)			
		Avg. Mass	Inertia	Torque	0.35	0.4	0.45	0.5
Male	95% Age 45 (Max)	116	2.095	25.23648	22.21	28.87	36.39	44.76
Male	95% Age 65 (Max)	110	1.951	23.33696	22.06	28.67	36.14	44.46
Female	95% Age 45 (Max)	106	1.855	15.73888	15.65	20.34	25.63	31.53
Female	95% Age 65 (Max)	102	1.759	13.83936	14.51	18.86	23.77	29.24
	Free	RCW			Hip angle (degrees) for time (seconds)			
		Avg. Mass	Inertia	Torque	0.1	0.15	0.2	0.25
Male	95% Age 45 (Max)	116	2.095	29.574	2.173	4.849	8.513	13.44
Male	95% Age 65 (Max)	110	1.951	27.348	2.17	4.82	8.454	13.35
Female	95% Age 45 (Max)	106	1.855	18.444	1.55	3.391	6.053	9.34
Female	95% Age 65 (Max)	102	1.759	16.218	1.432	3.154	5.62	8.662
					Leg angle (degrees) for time (seconds)			
Male	95% Age 45 (Max)	116	2.095	29.574	32.52	72.57		
Male	95% Age 65 (Max)	110	1.951	27.348	30.23	67.16		
Female	95% Age 45 (Max)	106	1.855	18.444	20.53	44.93	80.2	
Female	95% Age 65 (Max)	102	1.759	16.218	18	39.62	70.61	





Appendix O: Isometric Torque Values

Isometric Torques (Nm)

	Right			Left	
Subject A	20.78	28.45	**Subject A**	25.54	19.59
	22.07	27.85		25.36	22.69
	20.04	25.44		25.82	21.37
Average	20.96333	27.24667	**Average**	25.57333	21.21667
±Error	2.054686	3.186241	**±Error**	0.463609	3.111356
	CCW	**CW**		**CCW**	**CW**
Subject B	25.19	49.38	**Subject B**	21.13	21.56
	33.15	44.24		21.9	26.02
	36.92	49.02		19.36	21.34
Average	31.75333	47.54667	**Average**	20.79667	22.97333
±Error	11.97685	5.738618	**±Error**	2.60479	5.281565