International Journal of EXERCISE SCIENCE

Original Research

Lack of Correlation Between Natural Pelvic Tilt Angle with Hip Range of Motion, and Hip Muscle Torque Ratio

MARIA C. HERRERA†1, TAL AMASAY‡1, and CLAIRE EGRET‡1

1College of Nursing and Health Sciences, Department of Sport and Exercise Sciences, Barry University, Miami Shores, FL, USA

†Denotes graduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 14(1): 594-605, 2021. Excessive anterior and posterior pelvic tilts (PT) angles are associated with overuse injuries of the lower limbs and of the lumbo-pelvic-hip complex. There is a lack of evidence that correlates anterior and posterior PT angles with limited hip internal rotation (IR) and external rotation (ER), and hip muscles torque ratios. The purpose of this study was to examine the correlation between averaged anterior/posterior PT angle in standing position and hip IR and ER range of motion (ROM), hip adductors and abductors (Add/Abd) torque ratio, and hip flexors and extensors (Flexor/Extensor) torque ratio. Twenty-six healthy participants participated in this study, fifteen females (22.0 ± 2.8 yrs, 163.5 ± 7.5 cm, 65.9 ± 10.4 kg) and eleven males (22.0 ± 2.2 yrs, 178.5 ± 4.5 cm, 78.4 ± 8.7 kg). Hip muscle torques were collected with an isokinetic dynamometer, five trials at 30 degrees per second ($deg \cdot s^{-1}$) and at 60 $deg \cdot s^{-1}$. The measurement of PT in standing natural position and hip IR and ER ROM in functional weight-bearing lunge position were recorded, using a 3D Motion Analysis System. There were no significant correlations between PT angle and hip IR and ER ($p \geq 0.05$), no significant correlations between PT angle and hip Add/Abd torque ratio ($p > 0.05$), and no significant correlations between PT angle and hip Flexor/Extensor torque ratio ($p > 0.05$). The measurement of PT angle in standing natural position was not associated with hip IR and ER ROM and hip Add/Abd and Flexor/Extensor torque ratios, in healthy population.

KEY WORDS: Hip external rotation, Hip internal rotation, Hip adductors/abductors torque, Hip flexors/extensors torque, Anterior pelvic tilt, Posterior pelvic tilt

INTRODUCTION

Injuries pertaining to the lumbo-pelvic-hip complex correspond to 14% of total lower limb injuries (15,16). The prevalence of injuries in this region is significantly lower when compared to the knee and ankle, 50% and 36% respectively (15,16). Nevertheless, these injuries pertaining to the lumbo-pelvic-hip complex, are not only very incapacitating but also involve extensive rehabilitation periods and lead to multiple lower limb pathologies (37, 33).

The force-couple of hip flexors and hip extensors muscles, located in the sagittal plane, plays an important role in the performance of the core and the rotation of the pelvis (30). The iliopsoas is the prime mover hip flexor. Its bilateral contraction produces either the rotation of the femur towards the pelvis, the rotation of the pelvis towards the femur, or both movements simultaneously. If the pelvis is not properly stabilized by the abdominal muscles, the force of the hip flexors can generate an anterior pelvic tilt (PT) rotation. Thus, limitation in hip flexors range of motion can restrict the posterior PT range of motion (30). The gluteus maximus is the prime mover hip extensor muscle when the trunk is held erect in standing position. Both gluteus maximus and abdominal muscles (except for transverse abdominis) act as co-contractors to produce posterior tilt of the pelvis (30, 49).

Additionally, both hip adductors and abductors muscles, located in the frontal plane, are the greatest contributors in the control of pelvis and hip movement. An important hip adductor is the adductor magnus and the prime hip abductors are gluteus medius, gluteus minimus, and tensor fasciae latae (30). Hip adductors and abductors muscles imbalances can lead to the occurrence of injuries in the lumbo-pelvic-hip complex. A study by Tyler et al (2001), measured the hip adductors and abductors (Add/Abd) torque ratio in hockey players with a manual testing device. They found that a hip Add/Abd torque ratio below 80% is a risk factor associated with the appearance of adductor strains (46). On the other hand, to the best of the authors knowledge there are no injury risk factors associated with hip flexors and extensors (Flexor/Extensor) torque ratio. However, the average hip Flexor/Extensor torque ratio in healthy population, between 18 and 70 years-old, using an isokinetic dynamometer at 60 degrees per second ($deg \cdot s^{-1}$) was found to be 70%, in both sexes (8).

Several studies measured the PT in healthy population in both sexes using radiography, while the subjects were in standing position. In a study by Eddine et al (2001) an average posterior PT of 6.7 deg was found in 22 out of 24 healthy subjects with a mean age of 31 years old (13). Other study found that the mean anterior PT was 11.9 deg for men and 10.3 deg for women in a sample of 49 subjects with an average age of 24 years old (24). Finally, for 112 individuals, age between 20 and 45 years old, the average anterior PT angle was 12.3 deg, ranging from -1 to 27.9 deg (48).

It was stated that anterior/posterior PT angle affects lower limb kinetic chain and vice versa (12). Subtalar pronation and supination, knee rotation, and hip rotation influence the anterior and posterior PT angle and lumbar lordosis. Excessive anterior PT increases the lumbar lordosis and is the consequence of abdominal muscle weakness and iliopsoas tightness, and excessive posterior PT reduces lordosis due to the hamstring pulling down the pelvis (31). Moreover, a positive correlation was found between internal rotation of the thigh and anterior PT ($r = 0.58$, $p < 0.001$) and between the external rotation of the thigh and posterior PT ($r = 0.58$, $p < 0.001$) (12).

Kinematic pelvic tilt imbalances are associated with overuse injuries of the lower limbs and of the lumbo-pelvic-hip complex during dynamic movement (31, 25, 43, 20).An excessive anterior PT causes a tightness in the hip flexors by the position of the femur in relative flexion. The flexion moment at the hip counter-produces an extension moment at the knee that may increase the risk for joint hyperextension, thus could lead to knee injury such as ACL tear (25). In a review study by Barwick et al. (2012), it was found that the presence of excessive pronated foot is associated with excessive internal rotation of the tibia and femur, knee valgus, and anterior PT (2, 50). Whereas, excessive pronated foot is linked with tibial stress fractures, medial tibial stress syndrome, knee pain, anterior cruciate ligament injury, and low back pain. Additionally, anterior PT implications include hip muscles strains, sciatic nerve compressions due to pelvis rotation, and sacroiliac and lumbosacral joint instability (2). On the other hand, there is evidence that the training of hip muscles followed by the instruction of neutral pelvic tilt through abdominal drawing-in maneuvers leads to improvements in muscle strength and activation, as well as pain relief in the low back area and surroundings tissues (38, 32, 27, 28, 9). However, no correlation has been made between hip muscles performance and natural PT.

To the best of our knowledge there is a lack of evidence that correlates anterior and posterior PT angles while standing in natural position with limited hip IR and ER ROM, and hip Flexor/Extensor and Add/Abd torque ratios. However, in clinical practice it is very common to assess PT during static postural analysis to identify excessive anterior or posterior imbalances (16). The purpose of this study was to examine the correlation between anterior/posterior PT and hip IR and ER ROM, and hip Flexor/Extensor and Add/Abd torque ratios. It was hypothesized that anterior PT, in the right and left limbs, is positively correlated with hip IR ROM and posterior PT is positively correlated with hip ER ROM. Posterior PT, in right and left limbs, is positively correlated with hip Add/Abd torque ratios, at both 30 deg $\cdot$ s^{-1} and 60 deg $\cdot$ s^{-1} velocities, and negatively correlated with hip Flexor/Extensor torque ratios, at both 30 deg $\cdot$ s^{-1} and 60 deg $\cdot$ s^{-1} velocities. Meaning, that as posterior PT increases, the hip Add/Abd torque ratios will increase, and hip Flexor/Extensor torque ratio will decrease.

METHODS

This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science (29).

Participants

A power analysis conducted with G*POWER 3.1 (Universitat Kiel, Germany) determined that 23 participants were needed in the present study for a correlation with a power of 0.80, with an effect size of 0.50 (medium, accessible for sample recruitment), a projection population/correlation of 0.50, and an $\alpha = 0.05$. After institutional review board approval (IRB) and written consent form, twenty-eight healthy students volunteered to participate in this study. Participants number 2 and 24 were removed from the sample because their data files were corrupted (Table 1). Each participant signed an informed consent form. Exclusion criteria for this study included participant feeling pain during full hip IR and/or ER ROM, participant suffering from acute hip injury, chronic hip injury, subacute chronic hip injury, and/or any lower back injury. Participants were also excluded from the study if they had hip or back surgery within the past year. Female participants were required to wear athletic shorts and a sports bra. Male participants were required to wear athletic shorts and no shirt. All participants were right side dominant. The criteria for each participant to determine their dominance was based on their kicking leg.

Table 1. Participant characteristics.

	# of Participants	Age ± SD (years)	Height ± SD (cm)	Mass ± SD (kg)
Males	11	22.0 ± 2.2	178.5 ± 4.5	78.4 ± 8.7
Females	15	22.0 ± 2.8	163.5 ± 7.5	65.9 ± 10.4
All	26	22.0 ± 2.5	171.0 ± 6.0	72.1 ± 9.5

Note: Values are presented as means ± standard deviations (SD).

Protocol

Three-dimensional maximal hip IR and ER ROM as well as natural PT angles were collected using an eight-camera digital optical motion capture system (Vicon MX-3 Oxford, United Kingdom), at 240 Hz. Sixteen retro-reflective markers were located on each participant, according to Plug-In Gait lower body. Markers were set on the anterior superior iliac spine, posterior superior iliac spine, lateral thigh, knee joint line, lateral shin, lateral malleolus, heel, and head of second metatarsal of the toe. Data processing was done with Vicon Nexus software (Hauppauge, NY, USA).Data analysis was completed through Microsoft Excel 2016 (Microsoft Excel Corporation, Redmond, WA, USA). Kinematic data were filtered using a Forth Order Woltring spline filter with a cutoff frequency of 20 Hz.

Isokinetic concentric hip abductors, hip adductors, hip extensors, and hip flexors torques were captured using a Biodex Isokinetic Dynamometer System 3 (Biodex Medical System, Shirley, New York), at angular velocities of 30 $deg \cdot s^{-1}$ and 60 $deg \cdot s^{-1}$. This last velocity was selected as it has been reported that it can reproduce greater concentric forces in isokinetic testing (41). As velocity increases during eccentric contraction, the force-production remains unchangeable or slightly increases, and it is a good representation of both concentric and eccentric force-production capabilities of the evaluated muscles (5). Furthermore, studies focused on assessing hip muscle torque in healthy young individuals (6) and in individuals with stroke (14, 19) found that a 30 $deg \cdot s^{-1}$ angular velocity was reliable and that the peak muscle torques generated at 30 $deg \cdot s^{-1}$ were similar to those generated at 60 $deg \cdot s^{-1}$ (6).

Participants completed all tests in one day. Tests were conducted in the Movement Analysis Center Laboratory and in the Human Performance Laboratory. The entire session was no longer than 60 minutes. At the beginning of the session, participants completed the consent form and filled out a questionnaire prior to any data collection. Height and weight measurement followed.

Prior to any experimental conditions, participants completed a five-minute warm-up on a stationary bicycle, at a resistance of 1 kg at 60 RPM. The hip muscle torques were recorded on the Biodex Dynamometer. The test consisted of two parts, the measurement of hip Add/Abd torques and the measurement of hip Flexor/Extensors torques. The order of execution of the tests was randomly selected for each participant. A rest period of five minutes between each test was provided. As it was a maximal torque test, the participants were required to avoid working out 24 hours before the execution of the trials. For hip Add/Abd muscles torque test, participants were standing facing the dynamometer with hip joint axis of rotation aligned with the dynamometer axis of rotation, in the frontal plane. The standing position was selected because it is more functional compared with the side-lying position, and the gravity effect is reduced (41). The dynamometer attachment arm was placed over the middle one third of the lateral thigh. Participants were instructed to hold at the top of the machine, to help stabilize. The investigator put her hands on the participant's waist to cue them on how to properly stabilize their hip and torso and to avoid any undesirable movement or posture during the test movement. The ROM was set by assigning zero degrees of Add when the hip is in neutral position. Then the participants were instructed to abduct the hip up to 45 deg. A set of five trials of concentric/concentric hip Add/Abd were recorded at angular velocities of 30 deg · s^{-1} and 60 deg · s^{-1}, for each leg. The participants were instructed to abduct the hip as hard and fast as possible and returned to the initial position in the same way. A rest interval of at least 30 seconds were held between each set.

For hip Flexor/Extensor muscle torques, participants were standing up to the side of the dynamometer with hip joint axis of rotation aligned with the dynamometer axis of rotation, at the sagittal plane. The attachment arm was placed over the middle one third of the lateral thigh. Participants rest the hand of the testing side on the top of the machine, and the other hand on their waist, to help stabilize. To set the participant´s ROM participants were instructed to flex the hip to 90 deg and then to extend the hip to 195 deg. A set of five trials of concentric/concentric hip Flexor/Extensor were recorded at angular velocities of 30 deg · s^{-1} and 60 deg · s^{-1}, for each leg. The participants were instructed to flex the hip as hard and fast as possible and returned to the initial position in the same way. A rest interval of at least 30 seconds was held between each set. The participants were instructed to maintain an erect position and to perform the motion without any compensatory movement. Those trials that were not performed correctly were done again. During the hip muscle torque test these movements included mostly bending or extending the trunk, and/or externally rotating the hip.

For the session at the Movement Analysis Center, sixteen pearlescent markers were attached with double-sided tape at various landmarks, as mentioned above, on the lower body of both dominant and non-dominant legs. These markers allowed for joint positions to be captured by the Vicon Motion Capture System (Oxford, United Kingdom). As required by the Vicon Nexus program in order to create participant computer models, participant leg length was measured bilaterally with a tape measure from ASIS to medial malleolus. Their ankle and knee width were also measured bilaterally with a caliper. After all measurements were made and markers were attached, participants were instructed to stand still in the preferred natural position for five seconds and the static PT rotation was collected (20).

Next, dynamic trials were captured. Participants were instructed to stand with hands overhead. Subsequently, participants were guided to a lunge position. With a goniometer assessment, the right knee was flexed approximately 25-35 deg from the goniometer arm, which was perpendicular to the lab floor. After the knee was placed in the correct angle, the hip was adjusted moving the participant's trunk forward. A hip flexion angle of 55 deg with respect to the goniometer arm, which was perpendicular to the lab floor, was assessed. The position was selected as it was functional, simulating joint position in running or changing direction and it required the participant to be weight bearing on the lower extremities (10, 44). In some dynamic positions, it is not possible to reach maximal IR and ER range of motion. This selected position, allowed us to control the movement and to avoid any other noise coming from different joints and muscles. Moreover, previous studies similarly selected the lunge position to assess hip range of motion, and to estimate hip joint center (40, 7, 45). A valslide apparatus (a sliding board) was placed under the front foot. Once the participants were in the lunge position, they were instructed to slide their foot toward IR and ER. The instruction was "rotate your foot internally and then rotate it externally to your maximum range of motion without rotating your pelvis and trunk". Each participant performed three trials per motion and per leg. The participants were instructed to maintain an erect position and to perform the motion without any compensatory movement. Those trials that were not performed correctly were done again. During the hip ROM test, compensatory movements included mainly trunk rotation instead of lower limb rotation.

Statistical Analysis

Data were compiled through Microsoft Excel 2016 (Microsoft Corporation, Albuquerque, New Mexico, USA).For hip Add/Abd and hip Flexor/Extensor torque tests, the three highest torque peaks of the five repetitions were averaged. For hip IR and ER ROM test, the angles of the hip were recorded at the end ROM for each direction in each trial. The maximal value of hip IR and ER for each limb, out of the three trials was used for the analysis. The measurement of PT from each static trial was analyzed by averaging the middle three seconds of the captured data. This was followed by statistical analysis, which was performed using SPSS Statistics Software Version 21 ® (IBM, Armonk, New York, USA). Pearson correlation tests were performed between every variable. Only significant correlations, with $p \leq 0.05$, were considered for analysis.

RESULTS

The descriptive statistics for the dependent variables are presented in Table 2. No significant correlations were identified between PT and all the other variables (Table 3).

Table 2. Descriptive statistics for the dependent variables.

Variable	Mean ± SD
R hip Flexor/Extensor Ratio at 30 deg · s^{-1}	1.08 ± 0.60
R hip Flexor/Extensor Ratio at 60 deg · s^{-1}	0.99 ± 0.60
L hip Flexor/ Extensor Ratio at 30 deg · s^{-1}	1.17 ± 0.50
L hip Flexor/Extensor Ratio at 60 deg · s^{-1}	1.05 ± 0.60
R hip Add/Abd Ratio at 30 deg · s^{-1}	0.95 ± 0.20
R hip Add/Abd Ratio at 60 deg · s^{-1}	0.78 ± 0.30
L hip Add/Abd Ratio at 30 deg · s^{-1}	0.91 ± 0.20
L hip Add/Abd Ratio at 60 deg · s^{-1}	0.84 ± 0.40
Neutral PT (deg)	5.73 ± 5.40
R Hip ER (deg)	17.56 ± 9.70
R Hip IR (deg)	14.97 ± 9.70
L Hip ER(deg)	20.27 ± 13.70
L Hip IR (deg)	14.78 ± 9.40

Note: Values are presented as means ± standard deviations (SD). R = right; L = left; deg = degrees; s = second; + = anterior pelvic tilt.

Table 3. Pelvic tilt correlations with hip internal rotation and external rotation range of motion and hip Flexor/Extensor and Add/Abd torque ratio.

Variables	Correlation and Significance
with hip Add/Abd R 30 deg · s^{-1}	r = -0.19 (p = 0.34)
with hip Add/Abd L 30 deg · s^{-1}	r = -0.17 (p = 0.38)
with hip Add/Abd R 60 deg · s^{-1}	r = -0.13 (p = 0.51)
with hip Add/Abd L 60 deg · s^{-1}	r = -0.12 (p = 0.55)
with hip Flexor/Extensor R 30 deg · s^{-1}	r = 0.32 (p = 0.10)
with hip Flexor/Extensor L 30 deg · s^{-1}	r = 0.06 (p = 0.75)
with hip Flexor/Extensor R 60 deg · s^{-1}	r = -0.07 (p = 0.70)
with hip Flexor/Extensor L 30 deg · s^{-1}	r = -0.19 (p = 0.33)
With R Hip ER	r = -0.11 (p = 0.58)
with L Hip ER	r = -0.25 (p = 0.21)
with R Hip IR	r = -0.16 (p = 0.43)
with L Hip IR	r = -0.02 (p = 0.89)

Note: R = right; L = left; deg = degrees; s = second; ER = external rotation; IR = internal rotation.

DISCUSSION

The purpose of this study was to examine the correlation between anterior/posterior PT, during natural upright standing, with hip IR and ER ROM, and hip Add/Abd and Flexor/Extensor torque ratios. Our first hypothesis was that anterior PT was positively correlated with hip IR. We rejected the first hypothesis. The correlation between PT angle and hip maximal IR ROM was weak and not significant for both limbs (r = -0.16, p = 0.43 for right limb, and r = -0.02, p = 0.89 for left limb). Our second hypothesis was that posterior PT was positively correlated with hip maximum ER ROM. The second hypothesis was rejected too. The correlation between PT angle and hip ER ROM was weak and not significant for both limbs (r = -0.11, p = 0.58 for right limb, and r = -0.25, p = 0.21 for left limb).

These findings may suggest that the measurement of PT angle while standing in the preferred natural position is not a good indicator for hip maximal IR ROM and hip maximal ER ROM in a lunge position in healthy population. This may lead us to think that clinicians must be cautious in the interpretation of the results when performing a postural analysis while standing in natural position in healthy population. Possible alterations seen in PT angle in natural standing position are not necessarily effectors on hip ROM in lunge position. Duval et al. (2010) found in their research that excessive foot pronation induced anterior PT whereas excessive foot supination induced posterior PT. The participants in the Duval et al. (2010) study were instructed to relax their hip and abdominal muscles while standing up quietly on top of a rotating platform, which oriented passively their feet both internally and externally. The PT angle was recorded during the lower limb internal and external rotations, and it was correlated with hip ROM (r = 0.58, p < .001) (12). This implies that PT angle may predict passive hip ROM during extreme lower limb external and internal rotations. The difference in findings between our study and Duval et al. (2010) study may be explained by the difference in methods used to measure the PT angle and IR and ER ROM. In our study, PT was measured in natural standing position, whereas maximal hip IR ROM and ER ROM were measured separately in a lunge position. Moreover, the maximal IR and ER ROM where measure while the individual actively performed maximal hip rotations. Our third hypothesis was that posterior PT was positively correlated with hip Add/Abd torque ratio, at both 30 deg · s^{-1} and 60 deg · s^{-1} velocities, and negatively correlated with hip Flexor/Extensor torque ratio, at both 30 deg · s^{-1} and 60 deg · s^{-1} velocities. We rejected the third hypothesis. The correlations between PT angle and hip Add/Abd torque ratio were weak and not significant at 30 deg · s^{-1} (r = -0.19, p = 0.34 for right limb, and r = -0.17, p = 0.38 for left limb) and 60 deg · s^{-1} (r = -0.13, p = 0.51 for right limb, and r = -0.12, p = 0.55 for left limb). Same was identified for hip Flexor/Extensor torque ratio at 30 deg · s^{-1} (r = 0.32, p = 0.10 for right limb, and r = 0.06, p = 0.75 for left limb) and 60 deg · s^{-1} (r = -0.70, p = 0.70 for right limb, and r = -0.19, p = 0.33 for left limb). Our study did not find correlation between hip muscle torque ratios and PT in natural standing position. Future research should look at the influence of maximum anterior PT and maximum posterior PT on maximal hip muscles torque ratios.

An interesting outcome that we found in our study was related to the Add/Abd torque ratio measured during the two different angular velocities. Our study found that the Add/Abd torque ratios at 30 deg · s^{-1} were 96.6% for the right limb and 89.5% for the left limb. Whereas at 60 deg · s^{-1} Add/Abd torque ratios decreased to 79.9% for the right limb and 79.7% for the left limb. Tyler et al. (2001) measured hip Add/Abd torque ratio in hockey players and found that a ratio lower than 80% was correlated with the occurrence of adductor strains (44). Their results are similar to our values; however, they used a manual testing device to measure the hip muscle torque in static position. This finding may indicate that clinicians need to use caution when interpreting hip Add/Abd torque ratios from static testing or dynamic testing using different angular velocities.

Our hip Flexor/Extensor torque ratio test results differ from a study by Calmels et al. (1997). Our findings showed an average value of 96.1% at 30 deg · s^{-1} and 87.9% at 60 deg · s^{-1} in the right limb, and 106.8% at 30 deg · s^{-1} and 90.5% at 60 deg · s^{-1} in the left limb. Whereas their results identified mean torque ratio of 65% for women and 72% for men, in a concentric mode at an angular velocity of 60 deg · s^{-1} (8). The differences between the two studies may be explained by the population sample, age range, and methods involved. Our population age was between 18 to 24 years old, while their population age was between 18 to 70 years old. We performed the hip muscle torque test in standing position, while they had participants performed it in a supine position.

The lack of correlations in our study between PT and hip IR and ER ROM and hip Add/Abd and Flexor/Extensor muscle torque ratio, may be related to the differences in pelves morphology. The study of Preece et al. (2008) found a standard deviation of 5 deg of ASIS-PSIS angle among a sample of 30 cadaver pelves. This difference can musk and weaken any correlation between PT and muscular and ligamentous forces (35). In order to control this pelvic morphology variability, future research may also consider the measurement of lumbar lordosis and hip joint angle. Finally, abdominal muscle strength was not assessed in this study. Future studies should focus on the measurements of abdominal muscles and gluteus maximus activation patterns and their influence on PT ROM.

There were few limitations in this study. We selected a lunge position to perform the maximal hip range of motion assessment. To the best of our knowledge, there are no previous validation studies that used this exact position for the evaluation of maximal hip ER and IR range of motion. However, the lunge position had been previously applied for hip joint center estimations (40), hip extension range of motion assessment (7), and maximum knee valgus/varus angles (45). The use of the Plug-In Gait model (PIG) by Vicon (Oxford, United Kingdom) for the estimation of PT, hip IR, and hip ER angles is another limitation. This biomechanical model includes the use of regression equations for hip joint center (22). While some authors argue that there are better methods for the hip joint center calculation, such as functional calibration approaches (23) or alternative equations (36, 17), the PIG model has been used not only in gait analysis (11) but also in the analysis of sport movements or gestures (39, 21, 26).The study of Kainz et al. (2017) found small differences in PT measurements in motion capture assessed through the PIG model (2.8 deg) compared with the Six-Degrees of freedom model (2.9 deg) (18). For the purpose of this study the researchers believe that the PIG model is still good to identify anterior/posterior PT and the hip max IR and ER rotations. The movement trend is still the same and should identify correlations if any.

Lastly, the value of PT found and the methods used to measure it might be another limitation. Our outcome showed an average PT value of 5.8 deg with a range from -5.4 deg to 13.1 deg. Previous studies measuring the PT angle in healthy general population found average values from 6.7 deg to 12.3 deg (13, 24, 48). These studies used radiography to measure the PT, while we used a 3D Motion Analysis System. Past research found weak to moderate correlations (r = 0.31, p = 0.002) between standing mean PT measurements recorded by radiography (6.6 deg) versus motion capture (12.1 deg), however our PT rotations are still under the spectrum of the other studies (34).

Measurement of PT angle in standing natural position in healthy population may not be a good predictor for maximal hip IR and ER ROM (in a standing lunge position) and hip Add/Abd and Flexor/Extensor muscle torque ratios. Future research may include the measurement of PT angles in dynamic/functional movement and their relation to hip IR and ER ROM deficiencies as well as hip Add/Abd and Flexor/Extensor torque ratios deficiencies. By better understanding the lower limbs' injury risk factors, future researchers, clinicians, and other health professionals can identify the risk factor of injury.

REFERENCES

1. Armpatzis A, Morey- Klapsing G, Karamanidis K, De Monte G, Stafildis S, Brugemann G. Differences between measured and resultant joint moments during isometric contractions at the ankle joint. J Biomech 38(4): 885-892, 2005.

2. Baker R. Globographic visualisation of three dimensional joint angles. J Biomech 44(10): 1885–1891, 2011

3. Baker R, Leboeuf F, Reay J, Sangeux M. The conventional gait model- success and limitations. Handbook of Human Motion. Cham, Switzerland: Springer International Publishing AG; 2018.

4. Barwick A, Smith J, Chuter V. The relationship between foot motion and lumbo-pelvic-hip function: A review of the literature. Foot 22(3): 224- 231, 2012 .

5. Boling MC, Padua DA, Creighton RA. Concentric and eccentric torque of the hip musculature in individuals with and without patellofemoral pain. J Athl Train 44(1): 7-13, 2009.

6. Burnett C, Filusch Betts E, King W. Reliability of isokinetic measurements of hip muscle torque in young boys. Phys Ther 70(4): 244-249, 1990.

7. Bushell J, Dawson S, Webster M. Clinical relevance of foam rolling on hip extension angle in a functional lunge position. J Strength Cond Res 29(9): 2397- 2403, 2015.

8. Calmels P, Nellen M, Van Der Borne I, Jourdin P. Concentric and eccentric isokinetic assessment of flexor-extensor torque ratios at the hip, knee, and ankle in a sample population of healthy participants. Arch Phys Med Rehabil 78(11): 1224-1230, 1997.

9. Carpes F, Reinehr F, Bolli C. Effects of a program for trunk strength and stability on pain, low back and pelvis kinematics, and body balance: A pilot study. J Bodyw Mov Ther 12(1): 22-30, 2008.

10. David E, Amasay T, Ludwig K, Shapiro S. The effect of foam rolling of the hamstrings on proprioception at the knee and hip joints. Int J Exerc Sci 12(1): 343-354, 2019.

11. Davis RB, Ounpuu S, Tyburski D, Gage J. A gait analysis collection analysis and reduction technique. Hum Mov Sci 10(5): 575-587, 1991.

12. Duval K, Lam T, Sanderson D. The mechanical relationship between the rearfoot, pelvis and low back. Gait & Posture 32(4): 637- 640, 2010.

13. Eddine TA, Migaud H, Chantelot C, Cotton A, Fontaine C, Duquennoy A. Variations of pelvic anteversion in the lying and standing positions: Analysis of 24 control participants and implications for CT measurement of position of a prosthetic cup. Surg Radiol Anat 23(2): 105–110, 2001

14. Eng J, Kim C, Macintyre D. Reliability of lower extremity strength measures in persons with chronic stroke. Arch Phys Med Rehabil 83(3): 322-328, 2002.

15. Gallo R, Plakke M, Sivis M. Common leg injuries of long-distance runners. Sports Health 4(6): 485- 495, 2012.

16. Harrington L. Assessment of degree of pelvic tilt within a normal asymptomatic population. Elsevier 16(6): 646- 648, 2011.

17. Harrington ME, Zavatsky AB, Lawson SE, Yuan Z, Theologis TN. Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging. J Biomech 40(3): 595–602, 2007.

18. Hsu A, Tang P, Jan M. Test-retest reliability of isokinetic muscle strength of the lower extremities in patients with stroke. Arch Phys Med Rehabil 83(8): 1130-1137, 2002.

19. Kainz H, Graham D, Edwards J, Walsh H, Maine S, Boyd RN, Lloyd DG, Modenese L, Carty CP. Reliability of four models for clinical gait analysis. Gait & Posture 54(1): 325-331, 2017.

20. Kendall FP, McCreary EK, Provance PG: Muscles: Testing and function, Baltimore, MD: Williams and Wilkins; 1993.

21. King E, Richter C, Franklyn-Miller A, Wadey R, Moran R, Strike S. Back to normal symmetry? Biomechanical variables remain more asymmetrical than normal during jump and change-of-direction testing 9 months after anterior cruciate ligament reconstruction. Am J Sports Med 47(5): 1175-1185, 2019

22. Lamontagne M, Mantovani G. How different marker sets affect joint angles in inverse kinematics framework. J Biomech Eng 139(4): 1-7, 2017.

23. Leardini A, Sawacha Z, Paolini G, Ingrosso S, Nativo R, Benedetti MG. A new anatomically based protocol for gait analysis in children. Gait Posture 26(4): 560–571, 2007.

24. Legaye J, Duval- Beaupere G, Hecquet J, Marty C. Pelvic incidence: A fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. Eur Spine J 7(2): 99-103, 1994.

25. Loudon J, Jenkins W, Loudon K. The relationship between static posture and ACL injury in female athletes. JOSPT 24(2): 91-97, 1996.

26. Marshall BM, Franklyn-Miller AD, King EA, Moran KA, Strike SC, Falvey EC. Biomechanical factors associated with time to complete a change of direction cutting maneuver. J Strength Cond Res 28(10): 2845-2851, 2014

27. Mills J, Taunton J, Mills W. The effect of a 10-week training regimen on lumbo-pelvic stability and athletic performance in female athletes: A randomized- controlled trial. Phys Ther Sport 6(2): 60-66, 2005.

28. Nadler S, Malanga G, Bartoli L, Feinberg J, Prybicien M, Deprince M. Hip muscle imbalance and low back pain in athletes: Influence of core strengthening. Med Sci Sports Exerc 34(1): 9-16, 2001.

29. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1-8, 2019.

30. Neumann D. Kinesiology of the hip: A focus on muscular actions. J Orthop Sports Phys Ther 40(2): 82-94, 2010.

31. Norris CM. Abdominal muscle training in sport. Br J Sp Med 27(1): 19-27, 1993.

32. Oh J, Cynn H, Won J, Kwon O, Yi C. Effects of performing an abdominal drawing-in maneuver during prone hip extension exercises on hip and back extensor muscle activity and amount of anterior pelvic tilt. J Orthop Sports Phys Ther 37(6): 320-324, 2007.

33. Opar D, Williams M, Shield A. Hamstring strain injuries: Factors that lead to injury and re-injury. Sports Med 42(3): 209- 226, 2012.

34. Pesenti S, Prost S, Blondel B, Pomero V, Severyns M, Roscigni L, Authier G, Viehweger E, Jouve J. Correlations linking static quantitative gait analysis parameters to radiographic parameters in adolescent idiopathic scoliosis. J Orthop Trauma 105(3): 541-545, 2019.

35. Preece S, Willan P, Nester C, Graham-Smith P, Herrington L, Bowker P. Variation in pelvic morphology may prevent the identification of anterior pelvic tilt. J Man Manip Ther 16(2): 113-117, 2008.

36. Sangeux M, Peters A, Baker R. Hip joint centre localization: Evaluation on normal subjects in the context of gait analysis. Gait Posture 34(3): 324–328, 2011.

37. Schache A, Blanch P, Murphy A. Relation of anterior pelvic tilt during running to clinical and kinematic measures of hip extension. Br J Sports Med 34(4): 279-283, 2000.

38. Sharrock C, Cropper J, Mostad J, Johnson M, Malone T. A pilot study of core stability and athletic performance: Is there relationship? Int J Sports Phys Ther 6(2): 63-74, 2011.

39. Scott K, Robinson MA, Daniels K. Comparison of Plug- In Gait and Six Degrees of Freedom Model for estimating of kinematics during a double leg drop jump. NMU Commons 38(1): 692- 695, 2020.

40. Sinclair J, Bottoms L. Methods of determining hip joint center: Their influence on the 3D- kinematics of the hip and knee during the fencing lunge. Hum Mov14(3): 229-237, 2013.

41. Sugimoto D, Mattacola C, Mullineaux D.R, Palmer TG, Hewett T. Comparison of isokinetic hip abduction and adduction peak torques and ratio between sexes. Clin J Sport Med 24(5): 422-428, 2014.

42. Takaki S, Kaneoka K, Okubo Y, Otsuka S, Tatsumara M, Shiina I, Miyakawa S. Analysis of muscle activity during active pelvic tilting in sagittal plane. Phys Ther Res 19(1): 50-57, 2016.

43. Tateuchi H, Taniguchi M, Mori N, Ichihashi N. Balance of hip and trunk muscle activity is associated with increased anterior pelvic tilt during prone hip extension. J Electromyog Kinesiol 22(3): 391-397, 2012.

44. Thelen D, Chumanov E, Hoerth D, Best T, Swanson S, Young M, Heiderscheit B. Hamstring muscle kinematics during treadmill sprinting. Med Sci Sports Exer 37(1): 108- 114, 2005.

45. Thijs Y, Van Tiggelen D, Willems T, De Clercq D, Witvrouw E. Relationship between hip strength and frontal plane posture of the knee during a forward lunge. Br J Sports Med 41(11): 723-727, 2007.

46. Tyler TF, Nicholas SJ, Campbell RJ, McHugh, M. The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. Am J Sports Med 29(2): 124-128, 2001.

47. Van Der Bogert A, Read L, Nigg B. A method for inverse dynamic analysis using accelerometry. J Biomech 29(7): 949-954, 1996.

48. Vaz G, Roussouly P, Dimnet J. Sagittal morphology and equilibrium of pelvis and spine. Eur Spine J 11(1): 80-87, 2012.

49. Wilson E. Rehab tips: core stability: Assessment and functional strengthening of the hip abductors. Strength Cond J 27(2): 21-23, 2005.

50. Willson J, Dougherty C, Ireland M, McClay Davis I. Core stability and its relationship to lower extremity function. J Am Acad Orthop Surg 13(5): 316–325, 2005.