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Short communication

The effect of using different coordinate systems on in-vivo hip angles can be estimated from computed tomography images

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ABSTRACT

Measurements of hip kinematics inherently depend on the coordinate system in which they are derived, yet the effect of the coordinate system definition on calculations of hip angles is not well-understood. Herein, hip angles calculated during dynamic activities were compared using coordinate systems described in the literature. In-vivo kinematic data of 24 participants (13 males) were analyzed during gait and the anterior impingement test using dual fluoroscopy and model-based tracking. Two coordinate systems for the pelvis (anterior pelvic plane, International Society of Biomechanics [ISB]) and three coordinate systems for the femur (table top plane with two definitions of the superior-inferior axis, ISB) were evaluated. Bony landmarks visible on computed tomography (CT) images were identified to establish each coordinate system and used as the basis to calculate differences in hip angles between coordinate system pairs. In the analysis during gait, the maximum differences derived from various coordinate system definitions were 6.7° ± 5.5° for flexion, 7.7° ± 2.1° for rotation, and 5.5° ± 0.7° for adduction. For the anterior impingement test, the differences were 8.1° ± 5.9°, 7.1° ± 1.2°, and 5.3° ± 0.7°, respectively. Landmark-based analysis using CT images could estimate these dynamic differences with errors less than 1.0°. Our results indicate that hip angles can be accurately transformed to angles calculated in different coordinate systems by accounting for the inherent bony anatomy. This information may aid in the interpretation of results across biomechanical studies of the hip.

1. Introduction

Deleterious hip kinematics may result in debilitating diseases such as osteoarthritis. Thus, kinematic studies of the hip provide an important contribution to the literature. There are several coordinate systems that are utilized when analyzing kinematic data, such as those defined by the International Society of Biomechanics (ISB) (Wu et al., 2002) and the anterior pelvic plane (pAPP) (McKibbin, 1970). Of course, the value of a kinematic measurement will depend on the coordinate system in which it is derived. Unfortunately, there is a paucity of data demonstrating the effect of using different coordinate systems to measure hip kinematics. Yet, this information is needed to make accurate interpretations of kinematic data published across the literature. The purposes of this study were: (1) to calculate hip angles during dynamic activities using coordinate systems of the pelvis and femur that are commonly described in the literature, and (2) to determine if differences between coordinate systems could be estimated from computed tomography (CT) images by quantifying the differences in the position of anatomical landmarks in each coordinate system.

2. Methods

2.1. Activities and subjects

In-vivo kinematic data obtained during level walking and a supine anterior impingement test were analyzed. Gait was selected for this analysis as it is a very common activity of daily living that is frequently studied. The anterior impingement test generates a large amount of hip flexion, adduction, and internal rotation, which enabled us to examine the effect of using different coordinate systems over a wide range of motion. For gait analysis, 18 participants (11 asymptomatic controls and 7 patients with femoroacetabular impingement syndrome) walked at their self-selected walking speed on an instrumented treadmill (Fiorentino et al., 2017; Uemura et al., 2018a). For the anterior impingement test,

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9 participants (6 controls and 3 patients with femoroacetabular impingement syndrome) were examined (Kapron et al., 2015). Three control participants were included in both analyses, leading to a total sample size of 24 participants (13 males, 11 females, mean age: 26 ± 5 years, height: 174.8 ± 10.2 cm, weight: 68.3 ± 13.9 kg, body mass index: 22.2 ± 2.9). All study procedures were approved by our Institutional Review Board.

2.2. Dual-fluoroscopy, computed tomography, and model-based tracking

A combined experimental and computational protocol that included dual-fluoroscopy, CT, and model-based tracking was used to calculate in-vivo hip kinematics using methods described elsewhere (Bey et al., 2006; Fiorentino et al., 2017; Kapron et al., 2014). Of note, the accuracy of model-based tracking for measuring hip kinematics using this system is 0.5 mm and 0.6° (Kapron et al., 2014).

2.3. Coordinate systems of the pelvis and the femur

The ISB coordinate system (pISB, Fig. 1a) and pAPP (Fig. 1b) were used to represent the pelvis (Table 1). For the femur, three coordinate systems were analyzed, the ISB coordinate system for the femur (fISB, Fig. 1c) and two definitions of the table top plane (fTTP, Fig. 1d) (Kingsley and Olmsted, 1948). As multiple superior-inferior axes definitions exist for the fTTP (Takao et al., 2018), the two axes definitions herein were based on a projection of the head center, fTTP(H) (Uemura et al., 2018a), and the trochanteric fossa, fTTP(F) (Uemura et al., 2018b) (Table 1). We selected these coordinate systems because they are often used in published biomedical studies of the hip.

Table 1
Coordinate systems of the pelvis and femur and the landmarks necessary for each system.

	International Society of Biomechanics (ISB)	Clinical
Pelvis	pISB • Bilateral ASIS landmarks • Center of PSIS landmarks	Anterior pelvic plane (pAPP) • Bilateral ASIS landmarks • Center of pubic tubercles
Femur	fISB • Femoral head center • Medial and lateral epicondyles	Table top plane (fTTP) • Posterior greater trochanter • Medial and lateral posterior condyles • Projection of head center (H) or trochanteric fossa (F)

ASIS: anterior superior iliac spine.
PSIS: posterior superior iliac spine.
Landmarks necessary to define each coordinate system are listed in bullet points.

To identify the anatomical landmarks necessary to define each coordinate system, a host of candidate nodes on the bony surface that contained the landmark of interest was lassoed manually in Postview (v.2.0, University of Utah, Salt Lake City, UT). Then, the single node among the candidate list that represented the landmark of interest was found using Matlab (v.7.10, The MathWorks, Natick, MA). Specifically, the posterior superior iliac spine (PSIS) and anterior superior iliac spine (ASIS) were selected as the most

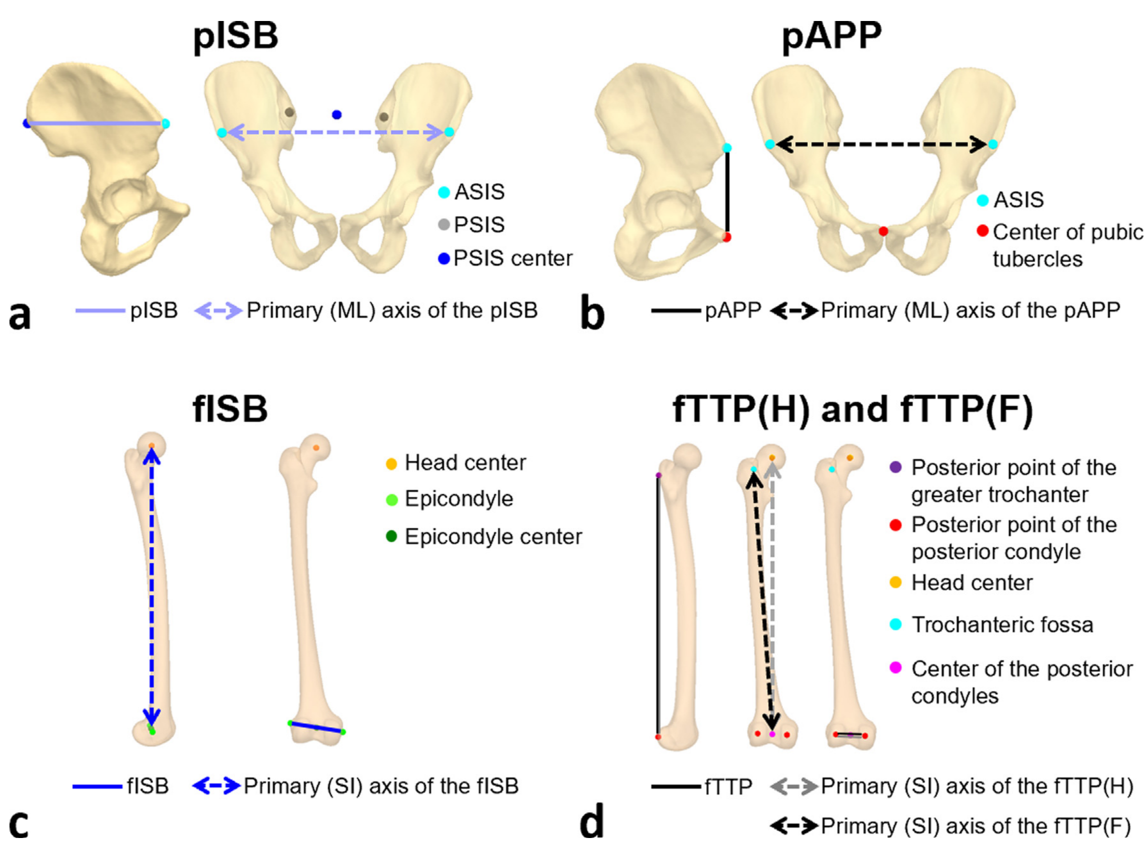

Fig. 1. Coordinate systems examined in this study for the pelvis (a and b) and femur (c and d). (a) The International Society of Biomechanics coordinates of the pelvis (pISB) included the bilateral anterior superior iliac spines (ASISs) and the center of the posterior superior iliac spines (PSISs). (b) The anterior pelvic plane coordinates of the pelvis (pAPP) included the bilateral ASISs and the center of the pubic tubercles. For the pISB and the pAPP, the medial-lateral (ML) axes were identical. (c) The ISB coordinates of the femur (fISB) included the head center and the medial and lateral epicondyles. (d) The table top plane coordinates of the femur (fTTP) included the most posterior points of the condyles and a projection of the head center (fTTP(H)) or the trochanteric fossa (fTTP(F)) onto the plane, which also contained the most posterior aspect of the greater trochanter.

posterior and anterior node, respectively. The pubic tubercle was selected as the most anterior node. The medial, lateral and posterior epicondyle was selected as the most medial, lateral, and posterior nodes, respectively. The posterior point of the greater trochanter was selected as the most posterior node. The trochanteric fossa, which was used for the superior-inferior axis of fTTP (F), was selected as the most lateral node.

For the femoral head center, PostView was used to identify all nodes representing the articulating surface based on measurements of curvature (Harris et al., 2013); these nodes were fit to a sphere in Matlab to identify the center of the femoral head. For the pelvis, the axis including the bilateral ASIS landmarks was defined as the primary axis in both the pAPP and the pISB. The secondary axis was defined between the mid-point of the ASIS landmarks and the center of the pubic tubercles for the pAPP and between the mid-point of the ASIS landmarks and the mid-point of the PSIS landmarks for the pISB. For the femur, the primary axis for the fTTP(H) was defined between the projection of the head center onto the fTTP and the center of the posterior condyles. The primary axis for the fTTP(F) was defined between the projection of the trochanteric fossa onto the fTTP and the center of the posterior condyles. For the fISB, the primary axis was defined between the head center and the center of the two epicondyles. The secondary axis was defined from the most posterior points of each condyle for both the fTTP definitions and between the medial and lateral epicondyles for fISB. For all coordinate systems, the tertiary axis was defined orthogonal to both the primary and secondary axes. Then, the secondary axis was reoriented based on the primary and tertiary axes to create an orthogonal coordinate system. As some previous studies have used a combination of ISB coordinates with the pAPP or the fTTP (Shoji et al., 2016), each of the two pelvic coordinate systems was evaluated with each of the three femoral coordinate systems (i.e. a total of six pairs).

To facilitate comparisons between participants, results from gait analysis were standardized to one gait cycle and results for the impingement test were standardized using the time point of first peak in flexion and the time point of maximum internal rotation in flexion (Kapron et al., 2015).

2.4. Landmark-based analysis of the local coordinate systems on the sagittal, axial, and coronal planes using CT images

The differences in the local coordinate systems were quantified on the sagittal, axial, and coronal planes using the bony landmarks of each coordinate system. The pAPP and the fTTP(H) were used as reference. For the pelvis, the only angular difference between pAPP and pISB existed on the sagittal plane as the medial-lateral axis for both coordinate systems was identical (Fig. 2a). Similarly, for the femur, the angle between fTTP(F) and fTTP(H) was determined on the coronal plane, as this plane definition was shared between the two coordinate systems. However, differences between the fISB and the fTTPs (i.e., fTTP(F) and fTTP(H)) existed on all three anatomical planes. On the sagittal plane, the angle between the fISB and fTPPs represented differences in the superior-inferior axis between the coordinate systems (Fig. 2a). On the axial plane, the angle between the anatomical transepicondylar axis and the fTTPs was calculated (Fig. 2b). The angle between the fISB and fTTPs was also calculated on the coronal plane of the femur (Fig. 2c).

2.5. Hip angle calculations

The observed differences in the landmark-based analysis of the local coordinate systems in each of the anatomical planes were used to approximate the dynamic difference in hip angles. Specifically, for flexion, sagittal plane differences between the pAPP and the pISB and between the fTTPs and the fISB were used to offset the dynamic hip angles and to estimate differences in flexion angles during dynamic motion (Fig. 2a); this yielded four coordinate system combinations with explicit differences in flexion since the fTTP coordinate systems are, by definition, identical in the sagittal plane. For rotation, the axial plane differences between the fISB and the fTTPs were used to offset the dynamic hip angles (Fig. 2b). For adduction, coronal angles between the superior-inferior axes of the three femoral coordinate systems were used to offset the dynamic hip angles (Fig. 2c). For clarity, each coordinate system combination was expressed in the order of the pelvic coodinate system, asterisk (*), femoral coordinate system (e.g. pAPP * fISB).

2.6. Statistics

Upon confirming a normal distribution using a Kolmogorov-Smirnov test in SPSS statistical software (v.22, IBM, Armonk, NY), results were expressed as mean ± standard deviation (SD). After the differences in dynamic hip angles across coordinate system combinations were offset by angles relative to the local coordinate systems, a one sample *t*-test was performed to assess if the mean offset dynamic angle for each subject was different from 0°.

3. Results

3.1. Landmark-based analysis of the local coordinate systems

For the 24 participants, the mean ± SD difference in pelvic coordinate systems was 5.7° ± 5.6° on the sagittal plane (Table 2). There was no difference on either the axial or the coronal plane as the medial-lateral axis was shared between the pISB and the pAPP. For the femoral coordinate systems, the difference was 1.1° ± 0.6° and 7.4° ± 1.9° on the sagittal and axial plane, respectively; no difference was found between the fTTP(F) and the fTTP(H) as the coronal plane of the fTTPs was shared (Table 2). On the coronal plane, a difference of 5.4° ± 0.7° was found between the fTTP(F) and fTTP(H) and a difference of 0.1° ± 0.2° was found between the fISB and the fTTP(H) (Table 2).

3.2. Gait

During the gait cycle, the largest flexion angle was found for the pISB * fTTP(H) and the smallest angle was found for the pAPP * fISB (Fig. 3a), resulting in a maximum mean difference of 6.7° ± 5.5° (Supplementary Table 1). For both rotation and adduction, the difference in angles was derived explicitly from the femoral coordinate system, as the pelvis coordinate systems did not vary in the axial or coronal plane. The largest internal rotation and adduction angles were found with the fTTP(F), and the smallest angles were found with the fISB (Fig. 3a), resulting in a maximum mean absolute difference of 7.7° ± 2.1° for rotation and 5.5° ± 0.7° for adduction (Supplementary Table 1).

3.3. Impingement test

During the impingement test, the combination of the coordinate systems that resulted in the largest and smallest flexion angles was the same as those during gait (i.e., largest: pISB * fTTP (H), smallest: pAPP * fISB) (Fig. 3b). The mean difference between the pISB * fTTP(H) and pAPP * fISB was 8.1° ± 5.9° (Supplementary Table 2). Again, the difference in rotation and adduction angles was derived explicitly from the femoral coordinate system. For rotation and adduction, the largest internal rotation and adduction angles were found when the fTTP(F) was selected and the smallest angles were found when the fISB was selected (Fig. 3b). The max-

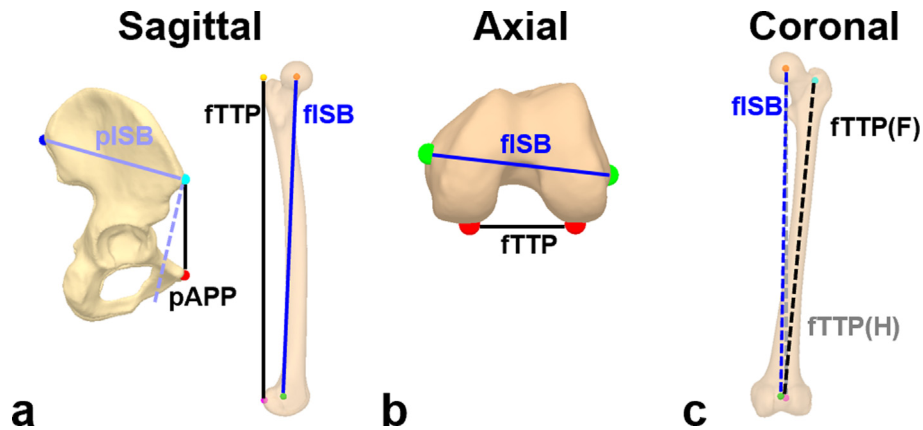

Fig. 2. Difference between the local coordinate systems on the three planes shown with a right hemi-pelvis and left femur. (a) Differences on the sagittal plane. For the pelvis, the angle between the anterior pelvic plane (pAPP, black) and the line perpendicular to the International Society of Biomechanics (ISB) plane (dotted light blue) was calculated. For the femur, the difference between the table top plane (fTTP, black) and the ISB coordinates of the femur (fISB, blue) was calculated. (b) Difference on the axial plane. The angle between the fISB (blue) and the fTTP (black) was calculated. (c) Differences on the coronal plane. Gray dotted line indicates the superior-inferior (SI) axis of the fTTP(H), black dotted line indicates the SI axis of the fTTP(F), and the blue dotted line indicates the SI axis of the fISB. The difference between each of the two SI axes was calculated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Differences in the local coordinate systems of the pelvis and femur quantified from computed tomography images.

	Sagittal plane		Axial plane*	Coronal plane*	
	Pelvis (pISB − pAPP)	Femur (fTTP − fISB)	Femur (fTTP − fISB)	Femur(fTTP(F) − fTTP(H))	Femur (fISB − fTTP(H))
Gait group (18 cases)	5.5 ± 5.5°	1.2 ± 0.6°	7.5 ± 2.1°	5.4 ± 0.7°	0.1 ± 0.2°
Impingement test group (9 cases)	7.1 ± 6.0°	1.0 ± 0.7°	7.1 ± 1.1°	5.3 ± 0.8°	0.1 ± 0.2°
Overall (24 cases**)	5.7 ± 5.6°	1.1 ± 0.6°	7.4 ± 1.9°	5.4 ± 0.7°	0.1 ± 0.2°

Data expressed as mean ± SD.
Positive angles indicate that the reference coordinate system (pAPP for the pelvis and fTTP(H) for the femur) results in smaller flexion, internal rotation, or adduction angles. pISB: coordinate system of the International Society of Biomechanics for the pelvis, pAPP: anterior pelvic plane, fTTP(F): table top plane with the superior-inferior axis using the projection of the trochanteric fossa, fTTP(H): table top plane with the superior-inferior axis using the projection of the head center, fISB: coordinate system of the International Society of Biomechanics for the femur.
* The pAPP and pISB have the same medial-lateral axis, and thus, differences between fTTP and fISB are only listed for the axial and coronal plane.
** Three cases were examined for both gait and the impingement exam.

imum mean absolute difference was 7.1° ± 1.2° for rotation and 5.3° ± 0.7° for adduction (Supplementary Table 2).

3.4. Angular difference from estimation

When dynamic hip angles calculated from each coordinate system were offset by the differences in the local coordinate systems (i.e., differences in anatomical landmark-based analysis using CT images), the mean difference for flexion, rotation, and adduction angles were all less than 0.6° for gait (Supplementary Table 1) and less than 1.0° for the impingement test (Supplementary Table 2). For both activities, there were some coordinate system combinations for which the mean offset dynamic angle was statistically different from 0° in a one sample *t*-test (Supplementary Tables 1 and 2).

4. Discussion

The selection of coordinate systems for the pelvis and femur caused angular variations in flexion, rotation, and adduction greater than 5.3° in all directions for the activities analyzed herein. While these differences may affect the clinical interpretation of results from biomechanical studies (van Arkel and Jeffers, 2016), we found that differences in hip angles could be estimated within 1.0° if differences in the local coordinate systems were considered. Our results should be considered when interpreting data across kinematics studies of the hip that are defined using the coordinate systems analyzed herein.

The maximum mean absolute differences found between the coordinate systems during the two activities were over 6° for flexion, 7° for rotation, and 5° for adduction. However, when the angles were offset based on the CT image data, dynamic angles between coordinate systems were calculated with differences less than 1.0°. While some angles were statistically different from 0° (Supplementary Tables 1 and 2), the differences were small and therefore are not likely to be clinically relevant. Thus, offsetting angles using subject-specific anatomical landmarks visible on CT images may be effective in estimating dynamic hip angles calculated in different coordinate systems.

Given our results, there is also potential to use generalized offsets to transform dynamic hip angles between different coordinate systems. For rotation and adduction, anatomical variation responsible for the differences was small (indicated by SD up to 2.1° in Table 2) and was similar to the findings of the previous reports (Beranger et al., 2018; Victor, 2009). Thus, a generalized offset may be used to transform the angles to other coordinate systems without substantial errors. For example, hip rotation calculated using the fTTP(H) or the fTTP(F) may be transformed to angles in fISB by subtracting a generalized offset of 7.4°. However, for flexion, anatomical variation responsible for the difference was larger. Specifically, the mean difference between the pelvic local coordinate systems on the sagittal plane was 5.7°, and, importantly, the SD was nearly as great as the magnitude of the difference (5.6°) (Table 2). Thus, it seems that a better measure of pelvic anatomical

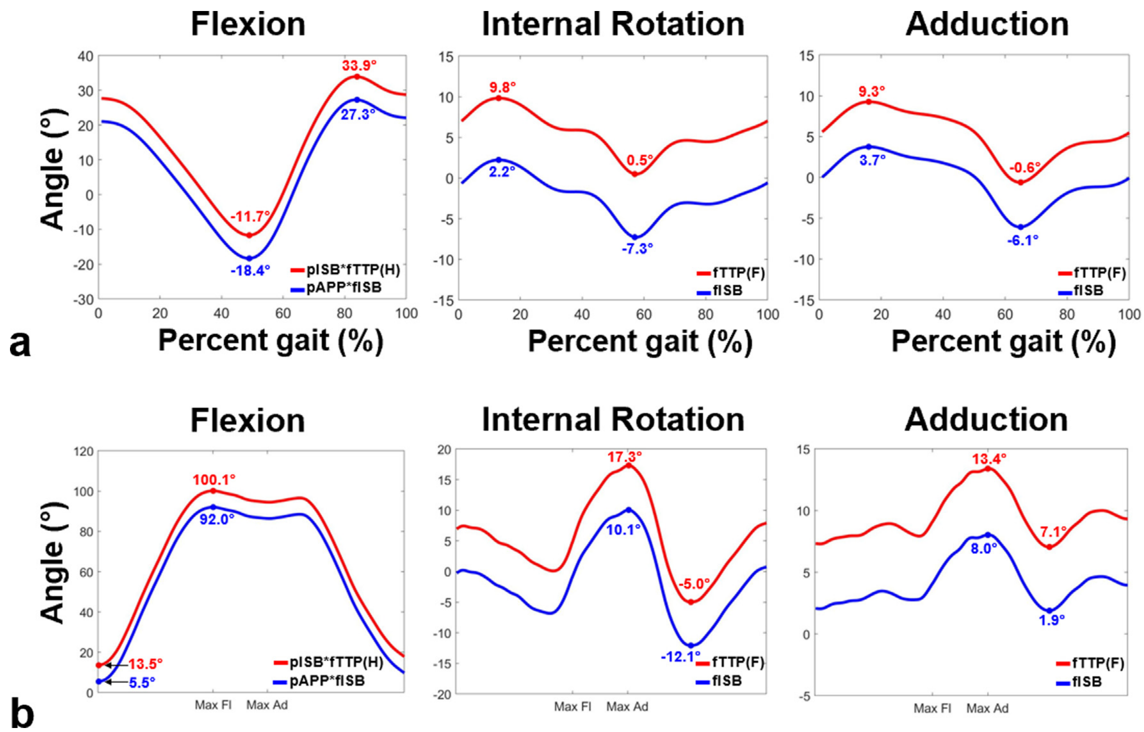

Fig. 3. The coordinate systems which resulted in the largest differences in hip joint angle calculations for each plane of motion during gait (a) and impingement test (b). For each plane, the largest and smallest angles are expressed by a red and blue line, respectively. The combination of the coordinate systems that resulted in the largest and smallest angle is listed in each figure. Angles in each figure express the maximum and minimum angle found during each activity. 'Max Fl' and 'Max Ad' in (b) indicate the time point of maximum flexion and maximum adduction during the anterior impingement test, respectively. pISB: coordinate system of the International Society of Biomechanics for the pelvis, fISB: coordinate system of the International Society of Biomechanics for the femur, pAPP: anterior pelvic plane, fTTP(H): table top plane using the projection of the head center, fTTP(F): table top plane using the projection of the trochanteric fossa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

variation is needed to transform flexion angles to other coordinate systems using a generalized offset. Pelvic anatomical variation between genders and across hip diseases should be assessed in future studies to evaluate the suitability of applying a generalized offset (Imai et al., 2018; Mallard et al., 2017).

5. Limitations

Our results may not be extendable to other coordinate system definitions. However, results were found to be consistent across several coordinate system definitions, and thus, we believe that similar conclusions would be obtained if other landmark-based coordinate systems were analyzed. Another limitation was that only two activities were considered. Activities that require greater hip extension and abduction than that achieved during gait or the impingement test may yield different results.

6. Conclusions

Hip angles can be accurately transformed to angles calculated in different coordinate systems by accounting for the position of bony landmarks. This information may aid in the interpretation of results across biomechanical studies of the hip.

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Declaration of Competing Interest

The authors have no conflict of interests related to this study.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.109318.

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