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Coordinate system requirements to determine motions of the tibiofemoral joint free from kinematic crosstalk errors

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ABSTRACT

The relative rigid body motions between the femur and the tibia (termed tibiofemoral kinematics) during flexion activities can provide an objective measure of knee function. Clinically meaningful tibiofemoral kinematics are defined as the six relative rigid body motions expressed in a joint coordinate system where the motions about and along the axes conform to clinical definitions and are free from kinematic crosstalk errors. To obtain clinically meaningful tibiofemoral kinematics, coordinate systems must meet certain requirements which neither have been explicitly stated nor in fact satisfied in any previous publication known to the author. Starting with the joint coordinate system of Grood and Suntay (1983) where motions conform to clinical definitions, the body-fixed axes must correspond to the functional (i.e. actual) axes in flexion-extension and internal-external axial rotation to avoid kinematic crosstalk errors in rotations and both functional axes must be body-fixed throughout knee flexion. To avoid kinematic crosstalk errors in translations, the origins of the femoral and tibial Cartesian coordinate systems, which serve as stepping stones for computing translations, must lie on the functional body-fixed axes. Neither the paper by Grood and Suntay nor the ISB recommendation (Wu et al., 2002) which adopted the joint coordinate system of Grood and Suntay explains these requirements. Indeed meeting these requirements conflicts with the ISB recommendation thus indicating the need for revision to this recommendation. Future studies where clinically meaningful tibiofemoral kinematics are of interest should be guided by the requirements described herein.

1. Introduction

The relative rigid body motions of the tibia with respect to the femur in six degrees of freedom (termed tibiofemoral kinematics) during flexion activities can provide an objective measure of knee function and have been used to characterize and compare knee function among various knee conditions such as healthy native, replaced (i.e. total knee replacement), osteoarthritic, and anterior cruciate ligament (ACL) deficient (Arauz et al., 2018; Defrate et al., 2006; Matsuki et al., 2017; Yamaguchi et al., 2009). Clinically meaningful tibiofemoral kinematics are defined as the six relative rigid body motions expressed in a joint coordinate system where the motions about and along the axes conform to clinical definitions and are free from kinematic crosstalk errors. When the femur and tibia are modeled as rigid bodies, three mutually orthogonal axes which compose a local Cartesian coordinate system are fixed in each bone and tibiofemoral kinematics can be determined in the context of these coordinate systems through flexion (Woltring, 1994). Because the resulting relative motions do not conform to clinical definitions however, Grood and Suntay in their classic paper introduced a joint coordinate system where the rotations about each axis and the translations along each axis conform to clinical definitions (Grood and Suntay, 1983). Subsequently this joint coordinate system was recommended by the International Society of Biomechanics (ISB) (Wu et al., 2002). However, neither the paper by Grood and Suntay nor the ISB recommendation state the requirements imposed on the joint coordinate system to obtain tibiofemoral kinematics which are free from kinematic crosstalk errors; thus the recommended joint coordinate system is subject to these errors. Furthermore, the literature is rife with variations on the recommended coordinate system. Not only are the resulting tibiofemoral kinematics generated from the various joint coordinate systems not clinically meaningful but also worthwhile comparison between studies is not possible. Hence the primary

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purpose of this paper is to explain the requirements to obtain clinically meaningful tibiofemoral kinematics and hence bring the limitations of the joint coordinate systems of Grood and Suntay and the ISB recommendation to light. Once these requirements are understood, a second purpose of the paper is to discuss considerations in meeting these requirements for healthy native knees, ACL-deficient knees, and replaced knees.

2. Joint coordinate system of Grood and Suntay

In their classic paper, Grood and Suntay set forth a joint coordinate system with application to the tibiofemoral joint of the human knee (Fig. 1). Their joint coordinate system consisted of two body-fixed axes, one fixed to the femur about which flexion-extension (FE) rotations occur and one fixed to the tibia about which internal-external (IE) axial rotations occur. The third axis was mutually perpendicular to the body-fixed axes but not fixed to either bone and so termed the 'floating' axis about which varus-valgus (VV) rotations occur. The body-fixed axes were defined based on anatomic landmarks.

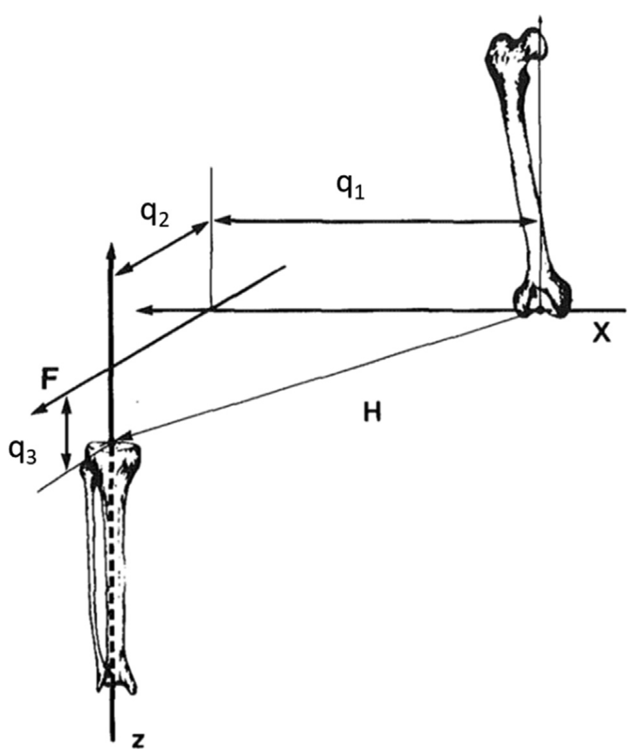

Fig. 1. Joint Coordinate System of Grood and Suntay (Grood and Suntay, 1983). The joint coordinate system consists of a body-fixed axis to the femur (X), a body-fixed axis to the tibia (z), and a floating axis (F) mutually perpendicular to the two body-fixed axes. Flexion-extension (FE) rotation occurs about X, internal-external (IE) axial rotation occurs about z, and varus-valgus (VV) rotation occurs about F. Medial-lateral (ML) translation occurs along X, compression-distraction (CD) translation occurs along z, and anterior-posterior (AP) translation occurs along F. The z axis coincides with the tibial mechanical axis and the origin of a Cartesian coordinate system fixed to the tibia is located on the z axis at the level of the subchondral bone between the tibial eminences. The X axis is perpendicular to the femoral sagittal plane and the origin of a Cartesian coordinate system fixed to the femur is located on the femoral mechanical axis at the most distal point midway between the femoral condyles. The projection of the vector **H** along each of the joint coordinate system axes corresponds to a clinical translation along that axis. The clinical translations are q_1 (medial/lateral (+)), q_2 (anterior (+)/posterior), and q_3 (compression (+)/distraction). Note that in Grood and Suntay, distraction translation was positive whereas in this paper compression is positive consistent with the positive direction of the z axis.

Translations were defined as motions along the respective joint coordinate system axes with medial-lateral (ML) translation occurring along the body-fixed axis of the femur, compression-distraction (CD) translation occurring along the body-fixed axis of the tibia, and anterior-posterior (AP) translation occurring along the floating axis and were determined in a two-step process. In the first step, femur-fixed and tibia-fixed Cartesian coordinate systems were defined. The relative location between their corresponding origins, which served as reference points, served to compute the vector **H** connecting the origins. In the second step, the vector **H** connecting the origins was projected along each of the joint coordinate system axes.

3. Requirements to obtain clinically meaningful rotations

For the tibiofemoral kinematics to be clinically meaningful, a requirement is that the body-fixed axes must correspond to the functional axes of joint rotation otherwise kinematic crosstalk in rotations will result (Piazza and Cavanagh, 2000). A functional axis is the 'true' or 'actual' axis about which rotation occurs and coincides, for example, with the axis of rotation when the axis is fixed in a body. To demonstrate kinematic crosstalk in rotations, two mechanical linkages were constructed, one with a simple revolute which moved in pure flexion-extension and another which moved in flexion-extension with coupled IE rotation (Piazza and Cavanagh, 2000). Depending on the orientation of the body-fixed axis of the femur, coupled IE rotation could be made to appear in the linkage with the simple revolute and made to disappear in the linkage which permitted the coupled motion. The authors therefore concluded that "avoidance of kinematic crosstalk error is possible if the chosen knee flexion axis coincides with the 'true' knee flexion axis." The magnitude of kinematic crosstalk in rotations was demonstrated by Most et al. (2004) who showed that internal tibial rotation with a geometric center axis in the femur (i.e. axis passing through the centers of circles fit to the posterior femoral condyles when superimposed in the sagittal view) versus the transepicondylar axis, which differed by only 4° on average

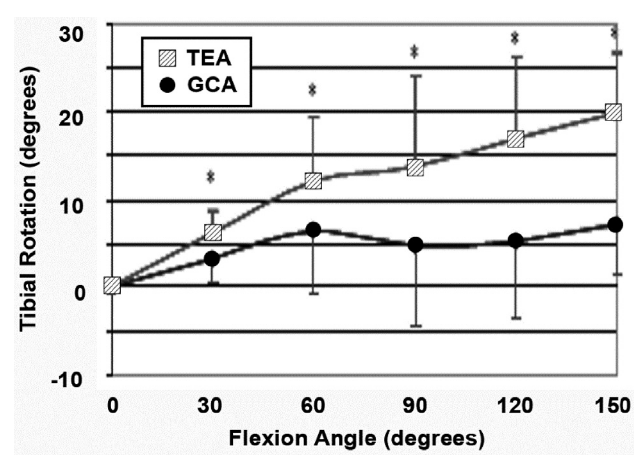

Fig. 2. Graphic representation of mean IE tibial rotation (internal positive) versus flexion angle in passive flexion with a body-fixed transepicondylar axis (TEA) versus a body-fixed mean geometric center axis (GCA) (adapted from Most et al., 2004). The GCA was found by fitting circles to the medial and lateral condyles and then connecting the centers of the circles with a line. The GCA closely approximates the functional body-fixed FE axis whereas the TEA does not (Eckhoff et al., 2007). Due to kinematic crosstalk in rotation, note the fundamental difference in patterns with internal rotation increasing monotonically for the TEA but not for the GCA. The IE rotation pattern with the TEA is the result of kinematic crosstalk, is erroneous, and is not clinically meaningful. Error bars represent one standard deviation from the mean.

from the geometric center axis, was 14° versus 5° on average, respectively, at 90° flexion (Fig. 2).

4. Requirements to obtain clinically meaningful translations

Since the location of the origins of the femoral and tibial Cartesian coordinate systems determine the translations based on the vector **H** which connects these origins in the scheme of Grood and Suntay, the location of the origins must be carefully considered. One requirement is that the origins lie on the functional body-fixed axes. As illustrated in Fig. 3, crosstalk errors in translations occur for an origin of a Cartesian coordinate system located on a body-fixed axis of the tibia not coinciding with the functional body-fixed IE axis.

Since IE rotation is relatively small compared to FE rotation, kinematic crosstalk errors resulting from the origin of the femoral Cartesian coordinate system not lying on the functional body-fixed FE axis can manifest as substantial errors in more than one translation (Fig. 4). To illustrate, consider the case where the femoral Cartesian coordinate system origin is distal to the functional body-fixed FE axis lying at the apex of the intercondylar notch (Fig. 4A). Assuming a radius of 23 mm of the cylindrical axis, which closely approximates the functional body-fixed FE axis (Pinskerova et al., 2014), and assuming a distal offset of 8 mm (Tanzer and Lenczner, 1990), the kinematic crosstalk errors in both distraction and posterior translations become 8 mm at 90° flexion (Fig. 4B).

Although kinematic crosstalk errors in translations can be avoided in the absence of VV rotations provided that the origins of the femoral and tibial Cartesian coordinate systems lie on the functional body-fixed FE and IE axes respectively, kinematic crosstalk errors introduced by VV rotation depend on the relationship of the functional VV axis to the functional body-fixed IE axis. If the functional VV axis intersects the functional body-fixed IE axis, then kinematic crosstalk errors can be eliminated provided that the origin of the tibial Cartesian coordinate system coincides with the point of intersection (Fig. 5A). If the functional VV axis does not intersect the functional body-fixed IE axis however, then kinematic crosstalk errors primarily in CD translations cannot be avoided (Fig. 5B). Practically, as long as contact is not lost between the tibial and femoral articular surfaces, VV rotation will be negligible. However, loss of contact has been reported in total knee replacements as described below in which case VV rotation may not be negligible.

A final consideration regarding the Cartesian coordinate system origins concerns establishing a reference where the translations are necessarily zero. This reference should be the tibiofemoral joint at extension (i.e. 0° flexion). If the functional body-fixed FE axis and the functional body-fixed IE axis intersect and VV rotation is negligible, then the femoral and tibial origins can coincide as in Fig. 5A for example and **H** = 0. Accordingly the translations are zero at the reference as necessary. If the femoral and tibial origins do not coincide as in Fig. 5B for example, then $\mathbf{H} \neq 0$ owing to the offset between the two origins in which case the translations at the reference are non-zero. Since non-zero translations at the reference do not represent relative motion between the tibia and femur but rather the offset between the two origins, any non-zero translations given by the projections of **H** along the joint coordinate system axes must be subtracted from the corresponding projections of **H'** where **H'** is the vector connecting the femoral and tibial origins after relative motion from the reference.

5. Summary of requirements for clinically meaningful tibiofemoral kinematics

(1) For the six relative rigid body motions to conform to clinical definitions, the joint coordinate system convention of Grood and Suntay is useful.
(2) To avoid kinematic crosstalk errors in rotations, the body-fixed FE and IE axes must be the functional axes and these axes must be fixed in the femur and tibia, respectively, throughout the activity under study.
(3) To avoid kinematic crosstalk errors in translations, the origins of the Cartesian coordinate systems must lie on the functional body-fixed FE and IE axes. If VV rotation is present, then the distance between the origin of the tibial Cartesian coordinate system and the functional VV axis must be minimized.
(4) The vector connecting the origins of the Cartesian coordinate systems must be used to determine translations by projecting the vector along the joint coordinate system axes.
(5) A tibiofemoral reference must be established with the knee in extension where rotations and translations are zero. Thus, if the vector connecting the Cartesian coordinate system origins at the reference is non-zero, then any non-zero (i.e. offset) translations must be subtracted from translations that occurred as a result of displacement from the reference.

With these requirements in mind, the limitations in the joint coordinate system of Grood and Suntay and the ISB recommendation which adopted this joint coordinate system can be appreci-

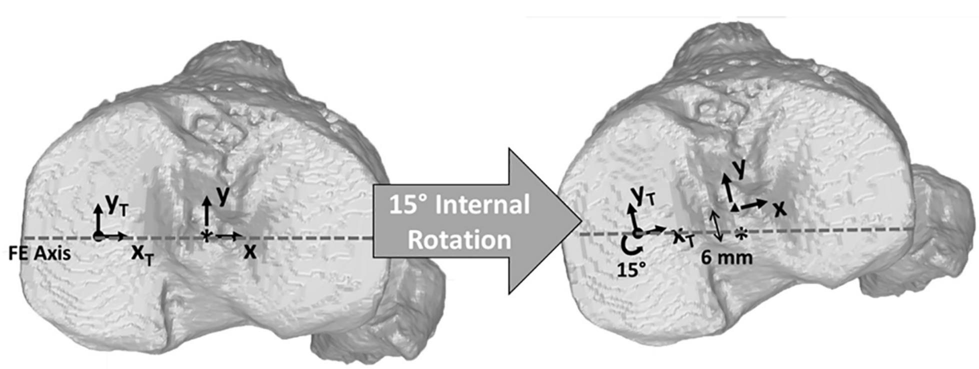

Fig. 3. Axial view of the tibial plateau showing two tibial Cartesian coordinate systems. In one coordinate system, the origin is centered between the tibial eminences per Grood and Suntay (1983) whereas in the other coordinate system the origin is approximately centered in the medial tibial plateau per Churchill et al. (1998). The z_T axis of the latter coordinate system coincides approximately with the functional body-fixed IE axis of the tibia. For an internal rotation of 15° about the z_T axis, the apparent anterior translation of the origin of the Cartesian coordinate system centered between the tibial eminences relative to a femoral Cartesian coordinate system origin which coincides with the intersection of the tibial mechanical axis and the body-fixed functional FE axis is 6(cos15°) mm anterior and 6(sin15°) mm medial indicative of substantial kinematic crosstalk primarily in anterior translation. This apparent translation is the result of kinematic crosstalk, is erroneous, and is not clinically meaningful.

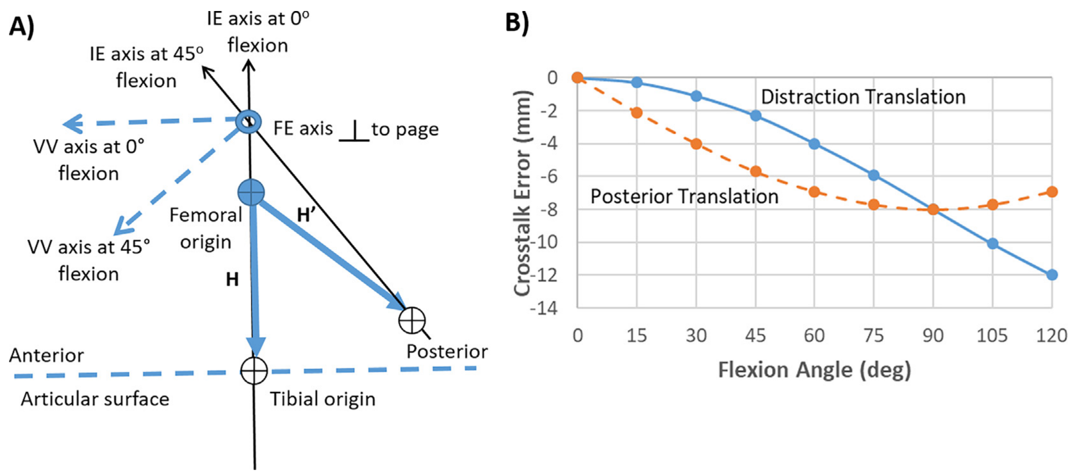

Fig. 4. Kinematic crosstalk errors in translations when the femoral Cartesian coordinate system origin does not lie on the functional body-fixed FE axis. A donut indicates a functional axis perpendicular to the page and crosshairs indicate a Cartesian coordinate system origin. (A) Line diagram in the sagittal view showing a femoral Cartesian coordinate system origin distal to the functional body-fixed FE axis and a tibial Cartesian coordinate system origin on the articular surface of the tibia with the joint coordinate system axes at 0° and 45° flexion. The magnitude of **H'** ≠ the magnitude of **H** indicating the presence of kinematic crosstalk errors. (B) Example kinematic crosstalk errors in translations for the case where the distal offset of the femoral Cartesian coordinate system origin from the functional body-fixed FE axis is 8 mm and the distance from the functional body-fixed FE axis to the tibial Cartesian coordinate system origin is 23 mm. Note that kinematic crosstalk errors in two translations become substantial because the knee moves through a relatively large angle in flexion.

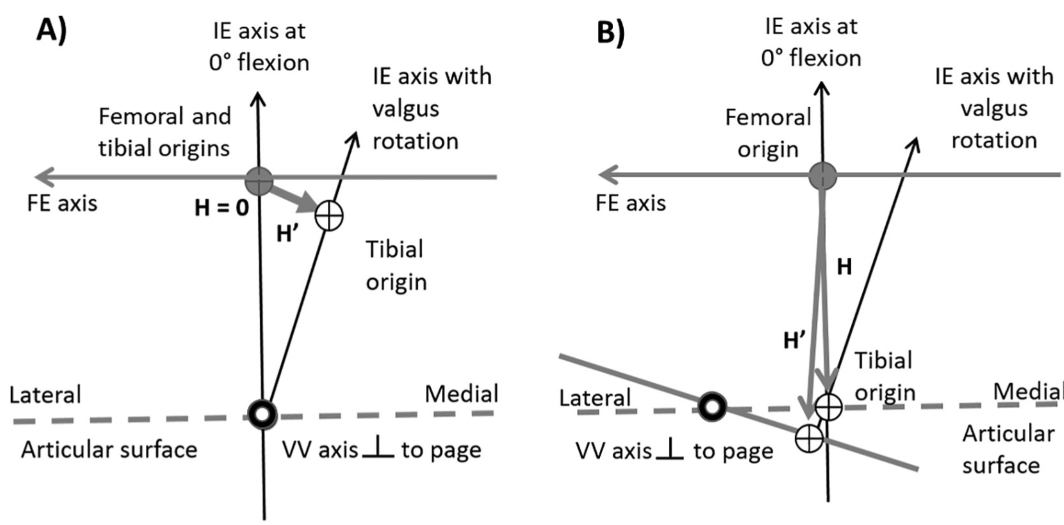

Fig. 5. Line diagrams in a coronal view illustrating kinematic crosstalk errors due to VV rotation. A donut indicates a functional axis perpendicular to the page and crosshairs indicate a Cartesian coordinate system origin. (A) If the functional VV axis intersects the functional body-fixed IE axis, then any offset of the tibial Cartesian coordinate system origin from the point of intersection introduces kinematic crosstalk errors primarily in medial–lateral translation. To illustrate, the femoral and tibial origins coincide at 0° flexion and **H = 0.** Valgus rotation causes the tibial origin to displace so that **H'** ≠ 0 indicative of kinematic crosstalk error. As the tibial origin moves distally closer to the intersection between the functional VV axis and the functional body-fixed IE axis, the kinematic crosstalk error steadily decreases and becomes zero when the tibial origin lies on the functional VV axis. (B) If the VV axis does not intersect the functional body-fixed IE axis, then kinematic crosstalk cannot be avoided since the vector **H'** will increase in length from **H**. For valgus rotation and the location of the tibial Cartesian coordinate system origin illustrated, kinematic crosstalk errors appear in distraction and lateral translations. Note that minimizing the distance between the functional VV axis and the tibial origin minimizes kinematic crosstalk errors.

ated. One limitation is that the body-fixed axes defined by Grood and Suntay do not correspond to the functional axes of the tibiofemoral joint and there is no mention of this requirement in the ISB recommendation. Indeed, the ISB recommendation states "the axes are defined based on bony landmarks that are either palpable or identifiable from X-rays." However, the precede body-fixed FE and IE axes as described below are not identifiable based on bony landmarks as required by the ISB recommendation.

Another limitation of the ISB recommendation concerns the relationship of the Cartesian coordinate system origins. The ISB recommendation calls for a common origin of both axis systems. This is problematic for two reasons. Per Requirement 3) above, the origins of the Cartesian coordinate systems must lie on the functional body-fixed FE and IE axes. However, the functional body-fixed FE and IE axes may not intersect in which case no common origin exists. Further, if VV rotation occurs, then the distance between the origin of the tibial Cartesian coordinate system and the functional VV axis must be minimized which generally would require that the origin of the tibial Cartesian coordinate system be offset from the origin of the femoral Cartesian coordinate system.

6. Native (i.e. Healthy intact) knee

Implicit to the use of the joint coordinate system by Grood and Suntay is that the functional body-fixed FE and IE axes are indeed fixed in the long bones. Since the publication of the paper by Grood and Suntay in 1983, research has identified the functional axes of the tibiofemoral joint and determined that these axes are indeed body fixed for the healthy native knee during the activities studied. Considering first the functional body-fixed FE axis of the femur, Hollister et al showed that during passive motion this axis intersected the origins of the collateral ligaments (Hollister et al., 1993). More recent research has demonstrated that the functional body-fixed FE axis of the femur is closely approximated by the axis of cylinders best fit to the posterior femoral condyles from about 15−110° of flexion during both passive motion (Eckhoff et al., 2005, 2007) and weight bearing flexion (Asano et al., 2005). Consequently the functional body-fixed FE axis passes approximately through the sulcus of the medial epicondyle and the prominence of the lateral epicondyle (Asano et al., 2005). Presumably the functional FE axis is body-fixed in gait but no study known to the author has demonstrated this. In any case, the functional body-fixed FE axis of the femur is positioned well superior and posterior to the body-fixed axis of the femur in Grood and Suntay which intersected the femoral mechanical axis at the most distal point midway between the femoral condyles (Fig. 6).

Considering next the functional body-fixed IE axis of the tibia, Hollister et al also located this axis and reported that it passed through the insertion of the anterior cruciate ligament during passive motion (Hollister et al., 1993) but this result applies when a distraction rather than compression force is transmitted by the joint because the experiment was conducted with the weight of the foot-shank applied. With a compressive force applied across the tibiofemoral joint by means of muscle tension, Churchill et al. (1998) showed that the functional body-fixed IE axis of the tibia intersected the medial tibial plateau, a finding later confirmed by others in passive motion (Freeman and Pinskerova, 2005), weight bearing flexion (Asano et al., 2005), and gait (Komistek et al., 2003). Thus the functional body-fixed IE axis of the tibia is positioned well medial to the body-fixed axis of the tibia in Grood and Suntay which coincided with the tibial mechanical axis passing through the midpoint between the tibial eminences (Fig. 6).

7. ACL-Deficient knee

Because determining tibiofemoral kinematics in anterior cruciate ligament (ACL) deficient knees (Defrate et al., 2006; Dennis et al., 2005; Li et al., 2006; Yamaguchi et al., 2009) is of interest, the effect of ACL deficiency on the functional axes should be understood. The effect of ACL deficiency has been studied both in vitro

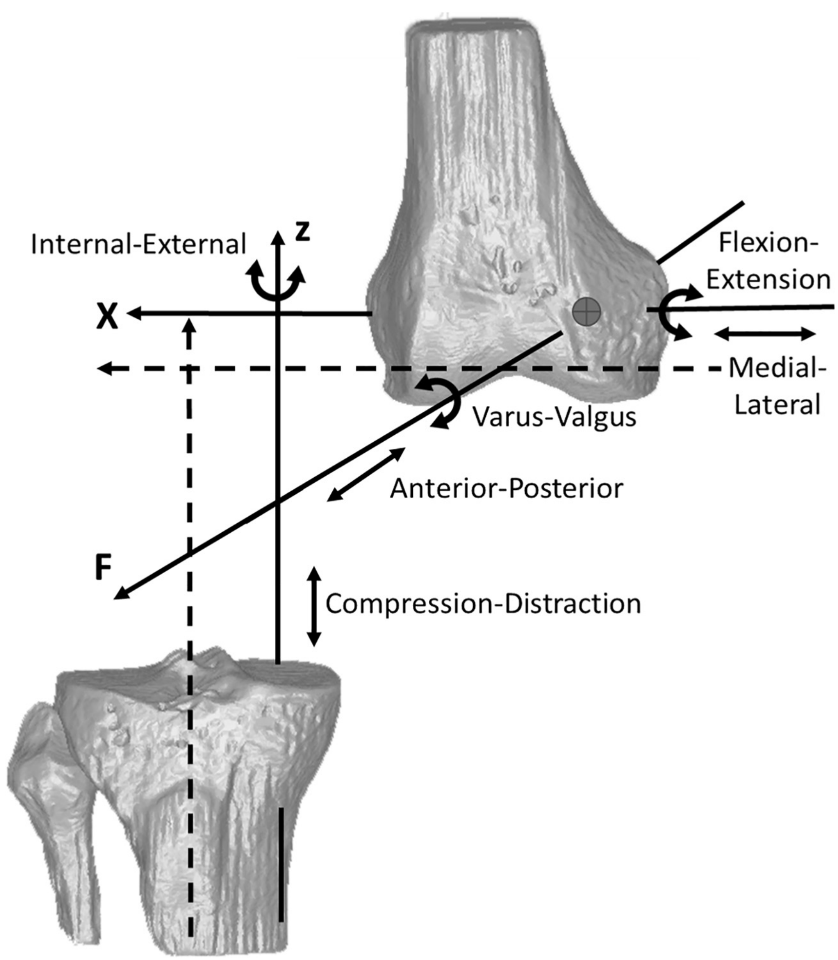

Fig. 6. Diagram illustrating the functional axes (solid lines) in relation to the body-fixed axes used by Grood and Suntay (dashed lines) (Grood and Suntay, 1983). For clarity, the bones are separated and for simplicity the three functional axes are assumed to intersect and to be orthogonal at the reference flexion angle (i.e. knee in extension) as indicated by the crosshairs symbol ⊕. The functional body-fixed FE axis of the femur is closely approximated by the cylindrical axis which is the axis of cylinders best-fit to the posterior femoral condyles from about 10−110° flexion (Eckhoff et al., 2005, 2007). The functional body-fixed IE axis of the tibia passes through the medial tibial plateau approximately parallel to the tibial mechanical axis (Churchill et al., 1998). Note that the functional axes, while approximately parallel to the body-fixed axes of Grood and Suntay, are shifted substantially in the respective bones. Thus, the body-fixed axes of Grood and Suntay do not meet the requirements for determining clinically meaningful tibiofemoral kinematics. Also note that neither functional axis can be identified based on palpable bony landmarks as required by the ISB recommendation. Finally, note that the functional axes may not intersect and that the functional axes may not be orthogonal at the reference flexion angle which is the knee at extension.

and in vivo using a number of modalities. In vitro modalities include an instrumented spatial linkage used in passive motion (Bonny et al., 2017) and a robotic testing system which applied various medial-lateral force and varus-valgus moments (Li et al., 2007). In vivo modalities include bi-planar fluoroscopy during single-leg lunge (Defrate et al., 2006), single-plane fluoroscopy during deep knee bend (Dennis et al., 2005), and video-based motion tracking during gait (Georgoulis et al., 2003). Regardless of modality and activity, noteworthy changes in motion patterns between intact and ACL-deficient knees were found. For example with the ACL resected, the functional body-fixed IE axis shifted medially by 2 mm on average (Bonny et al., 2017). However changes to the functional body-fixed IE axis in both ML position and the VV orientation varied widely emphasizing the need to determine the functional body-fixed IE axis on a patient-by-patient basis. In the deep knee bend, intact knees experienced posterior movement of the lateral femoral condyle on the tibial plateau and minimal movement of the medial femoral condyle with progressive knee flexion. In contrast, ACL-deficient knees experienced considerable posterior movement of the medial femoral condyle (Dennis et al., 2005). In gait, the IE rotation patterns were fundamentally different with internal rotation occurring during the early swing phase for intact knees and external rotation occurring for ACL-deficient knees (Georgoulis et al., 2003). Considering the differences in effects of ACL-deficiency during different loading conditions, not only must the functional IE axis be determined on an individual basis, but also this axis must be determined on an activity-specific basis as well. Further, it is unclear whether the functional axes are in fact body-fixed in ACL-deficient knees during activities other than passive motion so that this result remains to be demonstrated.

8. Replaced knees

Because total knee replacement (TKR) is a common surgical procedure and because one goal of the procedure is to restore knee function, tibiofemoral kinematics following TKR has been a topic of high interest (Arauz et al., 2018; Banks et al., 2005; Defrate et al., 2006; Guan et al., 2017; Mine et al., 2016; Moonot et al., 2009; Saevarsson et al., 2013). Analysis of tibiofemoral kinematics following TKR is challenging because of the many fundamentally different implant designs that are common in practice. Implant designs can be broadly categorized as mobile bearing and fixed bearing with the latter being more common. Within the fixed bearing category are posterior stabilized designs, posterior cruciate-retaining designs, bi-cruciate retaining designs, and medially constrained designs. Arguably, medially constrained designs are the most straightforward for determining clinically meaningful tibiofemoral kinematics because the functional IE axis is constrained to the center of the spherical socket in the medial compartment of the insert and hence is body-fixed to the tibia (Shimmin et al., 2015). However the functional FE axis must still be located and it must be demonstrated that it is body-fixed to the femur.

Not only must the functional FE axis of an arbitrary femoral implant design be found and demonstrated to be body-fixed to the femur, but also the functional IE axis of any insert design other than a medially constrained design must be found and demonstrated to be body-fixed to the tibia. This is because other insert designs typically have shallow concavities in both the medial and lateral compartments. As such, these designs permit AP movement of the femoral condyles in both compartments (Grieco et al., 2016; Komistek et al., 2008; Kuroyanagi et al., 2012) which possibly occurs as a result of both AP translation and IE rotation of the tibia. This is in contrast to the medially constrained insert which constrains AP translation of the tibia and permits primarily IE rotation. In fact, determining clinically meaningful tibiofemoral kinematics of insert designs with bilateral shallow concavities will be particularly challenging since the functional IE axis may not be body-fixed to the tibia as the knee is flexed.

Another complexity in determining clinically meaningful tibiofemoral kinematics following TKR develops in the event that loss of contact between either the medial or lateral articular surfaces occurs. Loss of contact also termed 'lift off' can be a relatively frequent event occurring more often in the lateral tibial compartment than the medial tibial compartment (Dennis et al., 2001). If loss of contact in either compartment is detected, then this event is evidence of varus or valgus rotation which may not be minimal in which case the functional VV axis must be considered. To avoid kinematic crosstalk in translations in the presence of VV rotation per the requirements above, the functional VV axis must intersect the functional body-fixed IE axis and the origin of the tibial Cartesian coordinate system must lie at the point of intersection. If the functional VV axis does not intersect the functional body-fixed IE axis however, then kinematic crosstalk in translations cannot be avoided (Fig. 5) but can be minimized by minimizing the distance in the coronal plane between the functional VV axis and the tibial Cartesian coordinate system origin. The magnitude of this error, which occurs primarily in CD translation, can be estimated. The worst-case error occurs when the functional VV axis lies in one tibial compartment and the functional body-fixed IE axis and tibial Cartesian coordinate system origin lies in the other tibial compartment. Considering that the maximum lift off distance is limited to 2.7 mm (Dennis et al., 2001), this distance becomes the worst case error and represents a distraction translation.

9. Overview of methods to locate functional body-fixed axes

Recognizing that the body-fixed axes must coincide with the functional axes to obtain clinically meaningful tibiofemoral kinematics, methods to locate the functional axes are of interest. Because a detailed review of these methods is not the purpose of this paper and because such reviews and/or comparisons of methods have been provided by other papers (Ehrig et al., 2007; MacWilliams, 2008; Passmore and Sangeux, 2016; Schache et al., 2006), an overview of available methods will be described here and appropriate papers cited. Aside from conventional methods which place external markers over the medial and lateral femoral epicondyles or attach a knee alignment device to the femoral epicondyles, all other methods to locate the functional axes impose a movement of the knee, measure the resulting motion by various means, and analyze the resulting motion to determine the functional axes. Accordingly these methods are termed functional methods. The various modalities used to measure motion include external devices such as an instrumented spatial linkage (Bonny et al., 2017) or an electromagnetic position sensor (Churchill et al., 1998), images acquired from bilateral radiographs (Asano et al., 2005; Sauret et al., 2016; Yin et al., 2015), MRI (Freeman and Pinskerova, 2005; Johal et al., 2005; Van Campen et al., 2011), or ultrasound (Passmore and Sangeux, 2016), and video-based motion tracking of skin-mounted markers (Baker et al., 1999; Cappozzo et al., 2005; Chang and Pollard, 2007; Ehrig et al., 2007; Gamage and Lasenby, 2002; Roland et al., 2011; Schache et al., 2006). The resulting motions have been analyzed using a variety of methods by imposing either a kinematic model with a single rotational axis (Chang and Pollard, 2007; Ehrig et al., 2007; Gamage and Lasenby, 2002) or a kinematic model with two rotational axes (Baker et al., 1999; Bonny et al., 2017; Churchill et al., 1998; Roland et al., 2011). Motions also have been analyzed based on geometrical relationships between the femur and tibia in images (Freeman and Pinskerova, 2005; Yin et al., 2015). Considering that the tibiofemoral joint has been demonstrated to have two functional body-fixed axes of rotation (Asano et al., 2005; Churchill et al., 1998; Hollister et al., 1993), ultimately a kinematic model with at least two rotational axes will be needed to locate both functional body-fixed axes.

Meeting the coordinate system requirements to determine clinically meaningful tibiofemoral kinematics in gait using video-based motion tracking of skin-mounted markers presents some difficulties. One difficulty surrounds the convention of using the femur mechanical axis as the primary (i.e. first) axis for establishing a medial-lateral axis which serves as the body-fixed FE axis. Using the femur mechanical axis as the primary axis places a constraint on the medial-lateral axis because this axis necessarily must be orthogonal to the primary axis. However, the functional FE axis in general will not coincide with the medial-lateral axis which meets this constraint. Accordingly using the medial-lateral axis as the body-fixed FE axis inherently introduces kinematic crosstalk errors into motions other than flexion-extension.

A second difficulty with using video-based motion tracking of skin-mounted markers concerns the soft tissue artifact. For video-based tracking of skin-mounted markers, several validation studies using various functional methods concluded that the DynaKAD method of analysis (Baker et al., 1999) gives a medial-lateral femoral axis which best approximates the functional FE axis (Passmore and Sangeux, 2016; Sauret et al., 2016; Schache et al., 2006). Although the DynaKAD method was best for approximating the functional FE axis, nevertheless the variability in the medial-lateral axis generated by the DynaKAD method was relatively large exceeding 15° (Passmore and Sangeux, 2016; Sauret et al., 2016). This variability is undesirable because misalignment of the medial-lateral axis with the functional FE axis will introduce kinematic crosstalk errors as noted above.

Given these difficulties, accurately determining clinically meaningful tibiofemoral kinematics in gait derived solely from video-based analysis of skin-mounted markers remains an ongoing challenge. Based on the second difficulty above, one study concluded that the use of an imaging technique may be required to locate the medial-lateral axis of the femur reliably prior to clinical decision making (Sauret et al., 2016). Considering these difficulties, it is apparent that improved methods are needed before tibiofemoral kinematics free from kinematic crosstalk errors can be reliably determined in gait studies involving video-based analysis of skin-mounted markers.

10. Summary

This paper has identified the requirements that must be satisfied to obtain clinically meaningful tibiofemoral kinematics. Clinically meaningful tibiofemoral kinematics are defined as the six relative rigid body motions expressed in a joint coordinate system where the motions about and along the axes conform to clinical definitions and are free from kinematic crosstalk errors. Neither the paper by Grood and Suntay (1983) nor the ISB recommendation (Wu et al., 2002) which adopted the joint coordinate system of Grood and Suntay explains these requirements. Indeed meeting these requirements is not possible following the ISB recommendation because of the need to identify body-fixed axes based on palpable bony landmarks and the need to establish a common origin for the femoral and tibial Cartesian coordinate systems. Thus, revision to this recommendation is warranted. Since these requirements neither have been stated explicitly nor have been satisfied in any previous study to the knowledge of the author, future studies where clinically meaningful tibiofemoral kinematics are of interest should be guided by the above requirements. If coordinate systems are used where the above requirements are not satisfied, then referring to the tibiofemoral motions using clinical terms is misleading in which case other terminology should be used to describe motions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Arauz, P., Peng, Y., Kwon, Y.M., 2018. Knee motion symmetry was not restored in patients with unilateral bi-cruciate retaining total knee arthroplasty-in vivo three-dimensional kinematic analysis. Int. Orthop. 42, 2817–2823.

Asano, T., Akagi, M., Nakamura, T., 2005. The functional flexion-extension axis of the knee corresponds to the surgical epicondylar axis: in vivo analysis using a biplanar image-matching technique. J. Arthroplasty 20, 1060–1067.

Baker, R., Finney, L., Orr, J., 1999. A new approach to determine the hip rotation profile from clinical gait analysis data. Hum. Movement Sci. 18, 655–667.

Banks, S.A., Fregly, B.J., Boniforti, F., Reinschmidt, C., Romagnoli, S., 2005. Comparing in vivo kinematics of unicondylar and bi-unicondylar knee replacements. Knee Surg. Sports Traumatol. Arthrosc. 13, 551–556.

Bonny, D.P., Howell, S.M., Hull, M.L., 2017. Changes in the rotational axes of the tibiofemoral joint caused by resection of the anterior cruciate ligament. J. Orthop. Res. 35, 886–893.

Cappozzo, A., Della Croce, U., Leardini, A., Chiari, L., 2005. Human movement analysis using stereophotogrammetry. Part 1: theoretical background. Gait Posture 21, 186–196.

Chang, L.Y., Pollard, N.S., 2007. Robust estimation of dominant axis of rotation. J. Biomech. 40, 2707–2715.

Churchill, D.L., Incavo, S.J., Johnson, C.C., Beynnon, B.D., 1998. The transepicondylar axis approximates the optimal flexion axis of the knee. Clin. Orthop. Relat. Res. 356, 111–118.

Defrate, L.E., Papannagari, R., Gill, T.J., Moses, J.M., Pathare, N.P., Li, G., 2006. The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis. Am. J. Sports Med. 34, 1240–1246.

Dennis, D.A., Komistek, R.D., Walker, S.A., Cheal, E.J., Stiehl, J.B., 2001. Femoral condylar lift-off in vivo in total knee arthroplasty. J. Bone Joint Surg. Br. 83-B, 33–39.

Dennis, D.A., Mahfouz, M.R., Komistek, R.D., Hoff, W., 2005. In vivo determination of normal and anterior cruciate ligament-deficient knee kinematics. J. Biomech. 38, 241–253.

Eckhoff, D., Hogan, C., DiMatteo, L., Robinson, M., Bach, J., 2007. Difference between the epicondylar and cylindrical axis of the knee. Clin. Orthop. Relat. Res. 461, 238–244.

Eckhoff, D.G., Bach, J.M., Spitzer, V.M., Reinig, K.D., Bagur, M.M., Baldini, T.H., Flannery, N.M., 2005. Three-dimensional mechanics, kinematics, and morphology of the knee viewed in virtual reality. J. Bone Joint Surg. 87-A (Suppl 2), 71–80.

Ehrig, R.M., Taylor, W.R., Duda, G.N., Heller, M.O., 2007. A survey of formal methods for determining functional joint axes. J. Biomech. 40, 2150–2157.

Freeman, M.A., Pinskerova, V., 2005. The movement of the normal tibio-femoral joint. J. Biomech. 38, 197–208.

Gamage, S.S., Lasenby, J., 2002. New least squares solutions for estimating the average centre of rotation and the axis of rotation. J. Biomech. 35, 87–93.

Georgoulis, A.D., Papadonikolakis, A., Papageorgiou, C.D., Mitsou, A., Stergiou, N., 2003. Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. Am. J. Sports Med. 31, 75–79.

Grieco, T.F., Sharma, A., Komistek, R.D., Cates, H.E., 2016. Single versus multiple-radii cruciate-retaining total knee arthroplasty: an in vivo mobile fluoroscopy study. J. Arthroplasty 31, 694–701.

Grood, E.S., Suntay, W.J., 1983. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J. Biomech. Eng. 105, 136–144.

Guan, S., Gray, H.A., Schache, A.G., Feller, J., de Steiger, R., Pandy, M.G., 2017. In vivo six-degree-of-freedom knee-joint kinematics in overground and treadmill walking following total knee arthroplasty. J. Orthop. Res. 35, 1634–1643.

Hollister, A.M., Jatana, S., Singh, A.K., Sullivan, W.W., Lupichuk, A.G., 1993. The axes of rotation of the knee. Clin. Orthop. Relat. Res. 290, 259–268.

Johal, P., Williams, A., Wragg, P., Hunt, D., Gedroyc, W., 2005. Tibio-femoral movement in the living knee. A study of weight bearing and non-weight bearing knee kinematics using 'interventional' MRI. J. Biomech. 38, 269–276.

Komistek, R.D., Dennis, D.A., Mahfouz, M., 2003. In vivo fluoroscopic analysis of the normal human knee. Clin. Orthop. Relat. Res. 410, 69–81.

Komistek, R.D., Mahfouz, M.R., Bertin, K.C., Rosenberg, A., Kennedy, W., 2008. In vivo determination of total knee arthroplasty kinematics: a multicenter analysis of an asymmetrical posterior cruciate retaining total knee arthroplasty. J. Arthroplasty 23, 41–50.

Kuroyanagi, Y., Mu, S., Hamai, S., Robb, W.J., Banks, S.A., 2012. In vivo knee kinematics during stair and deep flexion activities in patients with bicruciate substituting total knee arthroplasty. J. Arthroplasty 27, 122–128.

Li, G., Moses, J.M., Papannagari, R., Pathare, N.P., DeFrate, L.E., Gill, T.J., 2006. Anterior cruciate ligament deficiency alters the in vivo motion of the tibiofemoral cartilage contact points in both the anteroposterior and mediolateral directions. J. Bone Joint Surg. Am. 88-A, 1826–1834.

Li, G., Papannagari, R., DeFrate, L.E., Yoo, J.D., Park, S.E., Gill, T.J., 2007. The effects of ACL deficiency on mediolateral translation and varus-valgus rotation. Acta Orthop. 78, 355–360.

MacWilliams, B.A., 2008. A comparison of four functional methods to determine centers and axes of rotations. Gait Posture 28, 673–679.

Matsuki, K., Matsuki, K.O., Kenmoku, T., Yamaguchi, S., Sasho, T., Banks, S.A., 2017. In vivo kinematics of early-stage osteoarthritic knees during pivot and squat activities. Gait Posture 58, 214–219.

Mine, T., Hoshi, K., Gamada, K., Ihara, K., Kawamura, H., Kuriyama, R., Date, R., 2016. Kinematic analysis of posterior-stabilized total knee arthroplasty during standing up from and sitting down on a chair. J. Orthop. Surg. Res. 11, 142.

Moonot, P., Mu, S., Railton, G.T., Field, R.E., Banks, S.A., 2009. Tibiofemoral kinematic analysis of knee flexion for a medial pivot knee. Knee Surg. Sports Traumatol. Arthrosc. 17, 927–934.

Most, E., Axe, J., Rubash, H., Li, G., 2004. Sensitivity of the knee joint kinematics calculation to selection of flexion axes. J. Biomech. 37, 1743–1748.

Passmore, E., Sangeux, M., 2016. Defining the medial-lateral axis of an anatomical femur coordinate system using freehand 3D ultrasound imaging. Gait Posture 45, 211–216.

Piazza, S.J., Cavanagh, P.R., 2000. Measurement of the screw-home motion of the knee is sensitive to errors in axis alignment. J. Biomech. 33, 1029–1034.

Pinskerova, V., Nemec, K., Landor, I., 2014. Gender differences in the morphology of the trochlea and the distal femur. Knee Surg. Sports Traumatol. Arthrosc. 22, 2342–2349.

Roland, M., Hull, M.L., Howell, S.M., 2011. Validation of a new method for finding the rotational axes of the knee using both marker-based roentgen stereophotogrammetric analysis and 3D video-based motion analysis for kinematic measurements. J. Biomech. Eng. 133, 051003.

Saevarsson, S.K., Romeo, C.I., Anglin, C., 2013. Are static and dynamic kinematics comparable after total knee arthroplasty?. J. Biomech. 46, 1169–1175.

Sauret, C., Pillet, H., Skalli, W., Sangeux, M., 2016. On the use of knee functional calibration to determine the medio-lateral axis of the femur in gait analysis: Comparison with EOS biplanar radiographs as reference. Gait Posture 50, 180–184.

Schache, A.G., Baker, R., Lamoreux, L.W., 2006. Defining the knee joint flexion-extension axis for purposes of quantitative gait analysis: an evaluation of methods. Gait Posture 24, 100–109.

Shimmin, A., Martinez-Martos, S., Owens, J., Iorgulescu, A.D., Banks, S., 2015. Fluoroscopic motion study confirming the stability of a medial pivot design total knee arthroplasty. Knee 22, 522–526.

Tanzer, M., Lenczner, E., 1990. The relationship of intercondylar notch size and content to notchplasty requirement in anterior cruciate ligament surgery. Arthroscopy 6, 89–93.

Van Campen, A., De Groote, F., Bosmans, L., Scheys, L., Jonkers, I., De Schutter, J., 2011. Functional knee axis based on isokinetic dynamometry data: comparison of two methods, MRI validation, and effect on knee joint kinematics. J. Biomech. 44, 2595–2600.

Woltring, H.J., 1994. 3-D attitude representation of human joints: a standardization proposal. J. Biomech. 27, 1399–1414.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D'Lima, D.D., Cristofolini, L., Witte, H., Schmid, O., Stokes, I.Standardization, Terminology Committee of the International Society of Biomechanics, 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion–part I: ankle, hip, and spine. J. Biomech. 35, 543–548.

Yamaguchi, S., Gamada, K., Sasho, T., Kato, H., Sonoda, M., Banks, S.A., 2009. In vivo kinematics of anterior cruciate ligament deficient knees during pivot and squat activities. Clin. Biomech. 24, 71–76.

Yin, L., Chen, K., Guo, L., Cheng, L., Wang, F., Yang, L., 2015. Identifying the functional flexion-extension axis of the knee: an in-vivo kinematics study. PLoS ONE 10, e0128877.