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Short communication

Foot modeling affects ankle sagittal plane kinematics during jump-landing

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ABSTRACT

The foot-ankle complex is a key-element to mitigate impact forces during jump-landing activities. Biomechanical studies commonly model the foot as a single-segment, which can provide different ankle kinematics compared to a multi-segmented model. Also, it can neglect intersegmental kinematics of the foot-ankle joints, such as the hindfoot-tibia, forefoot-hindfoot, and hallux-forefoot joints, that are used during jump-landing activities. The purpose of this short communication was to compare ankle kinematics between a three- and single-segmented foot models, during forward and lateral single-leg jump-landings. Marker trajectories and synchronized ground reaction forces of 30 participants were collected using motion capture and a force plate, during multidirectional single-leg jump-landings. Ankle kinematics were computed using a three- (hindfoot-tibia) and a single-segmented (ankle) foot models, at initial contact (IC), peak vertical ground reaction force (PvGRF) and peak knee flexion (PKF). Repeated measures ANOVAs were conducted ($p < 0.05$). The findings of this study showed that during lateral and forward jump-landing directions, the three-segmented foot model exhibited lower hindfoot-tibia dorsiflexion angles (PvGRF and PKF, $p < 0.001$) and excursions (sagittal: $p < 0.001$; frontal: $p < 0.05$) during the weightbearing acceptance phase than the single-segmented model. Overall, the two foot models provided distinctive sagittal ankle kinematics, with lower magnitudes in the hindfoot-tibia of the three-segmented foot. Furthermore, the three-segmented foot model may provide additional and representative kinematic data of the ankle and foot joints, to better comprehend its function, particularly in populations whose foot-ankle complex plays an important role (e.g., dancers).

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1. Introduction

The foot-ankle complex is the link between the lower extremity and the ground (Brockett and Chapman, 2016). Its intricate structure (Russell et al., 2011; Stebbins et al., 2006; Wright et al., 2011) enables motion with considerable degree of joint stability (Brockett and Chapman, 2016). It also has an essential role to provide dynamic stability during the weightbearing acceptance phase (Towers et al., 2003). In many athletic and dance activities, the jump-landing movements are fundamental components (Liederbach et al., 2008; Tillman et al., 2004). Jump-landings are part of dancers training throughout years of practice. Dancers are

exposed to aesthetic and technical requirements during landing that other athletic populations do not have (e.g., toe-to-heel landing) (Liederbach et al., 2008; Orishimo et al., 2009). Furthermore, the landing phase requires dissipation of the kinetic energy generated during the jump phase (Tillman et al., 2004). Thus, the foot-ankle complex not only contributes to initially mitigate the forces transmitted to the body, but also influences the lower extremity biomechanics due to the closed kinetic chain (Decker et al., 2003; Donatelli, 1985; Hoch et al., 2015; Lee et al., 2018).

The different foot joints produce a challenging process to define *in vivo* foot kinematics (Okita et al., 2009). Recent research has shown clear evidence of how selection of marker data from different bones can influence the kinematics of a segment model (Nester et al., 2010). In previous landing biomechanical studies, the foot-ankle complex has often been modeled as a single-segment, linking the tibia to the foot (Decker et al., 2003; Orishimo et al., 2009; Schmitz et al., 2007). However, the bones within each segment of

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the foot move relative to each other (Nester et al., 2010). Higher ankle magnitudes have been reported using the single-segmented foot compared to multi-segmented models (De Ridder et al., 2015; Pothrat et al., 2015). While the single model is used to quantify foot-ankle kinematics, it neglects the physiological movements between and within the different foot segments (De Ridder et al., 2015; Pothrat et al., 2015; Stebbins et al., 2006). The Oxford Foot Model is one of the multi-segmented models that have been employed to investigate the foot-ankle kinematics, particularly the hindfoot-tibia (sagittal, frontal, transverse planes), forefoot-hindfoot (sagittal, frontal, transverse planes) and hallux-forefoot (sagittal plane) joints, providing information of a three-segmented foot (hindfoot, forefoot and hallux) (Stebbins et al., 2006; Wright et al., 2011). Previous literature has reported that different foot-ankle models can produce distinct ankle joint kinematics, which may lead to inaccuracies in the foot-ankle kinematic outputs (De Ridder et al., 2015; Pothrat et al., 2015). Currently, there is limited information on kinematic differences between multi- and single-segmented foot models during single-leg multi-directional jump-landings. Therefore, the purpose of this short communication was to investigate and compare ankle joint kinematics computed by a three- (hindfoot-tibia) and a single-segmented (ankle) foot models. We hypothesized that the hindfoot-tibia would provide lower angles and excursion magnitudes compared to the ankle of the single-segmented model.

2. Methods

2.1. Participants

A total of 30 participants (25.7 ± 5.7 years, 1.69 ± 0.07 m, 61.9 ± 10.1 kg) volunteered to participate in this study, after approval had been obtained from the Institutional Ethical Review Committee (BLINDED FOR REVIEW). Prior to testing, a written informed consent was obtained from each participant. They were required to be between 18 and 40 years old, and physically active with a minimum of 3 h/week of physical exercise, such as dance or recreational athletic activities/sports. If participants had a recent history of lower extremity injuries, any pain that would impair the ability to jump, lower extremity surgery within the past five years, or any known neurological/cognitive disorder, they were excluded from the study. The dominant lower extremity was determined as the preferred single-leg landing after performing a countermovement jump (Shimokochi et al., 2013).

2.2. Instrumentation and experimental procedures

Kinematic data of the dominant lower extremity were collected (200 Hz) with a 10-camera three-dimensional motion capture system (Opus, Qualisys AB, Gothenburg, Sweden). The ground reaction forces data were recorded (1000 Hz) using a Bertec force plate (FP4060, Bertec Corporation, Columbus, Ohio), and time-synchronized with the kinematic data. Thirty-three retro-reflective markers were placed on selected anatomical landmarks, and a four-marker cluster was used on the thigh of the dominant side. The markers of the foot-ankle complex were placed according to the Oxford Foot Model guidelines (Stebbins et al., 2006) [supplementary material]. Four calibration markers (medial femoral condyle and malleolus, upper posterior calcaneus, and first distal metatarsal) were removed prior to the jump-landing trials. Participants stood barefoot and wore a spandex short; and women wore sports bra. Before the static trial, a 5-minute self-directed warm-up was provided.

Participants stood on the non-dominant leg, 70 cm away from the center of the force plate (Wikstrom et al., 2008), then randomly

performed lateral (LJ) and forward (FJ) single-leg jump-landings (Taylor et al., 2016; Wikstrom et al., 2008), landed on the dominant leg, in the force plate center. Upon landing, participants immediately transitioned into a maximal vertical jump, followed by a second landing in the force plate center. After being familiarized with the task, participants completed three successful trials for each direction. A rest period of 30 s between trials was provided. Trials were excluded if participants lost balance, hopped, stepped off or shifted the dominant foot on the force plate; if they touched the force plate with the non-dominant foot; or if they removed their hands from the hips. For the current study, only the first landing was analyzed.

2.3. Data processing

After markers were manually identified using Qualisys Track Manager (Goteborg, Sweden), biomechanical data were exported to Visual 3D (C-Motion, Inc, Rockville, USA) for data processing. Based on the static trial, a 6-segment kinematic model composed by a pelvis, thigh, shank, hindfoot, forefoot and hallux was created for the multi-segmented model analysis (Carson et al., 2001); while a 4-segment kinematic model composed by a pelvis, thigh, shank and foot was created for the single-segmented model analysis. Oxford Foot Model kinematic data for the hindfoot-tibia were calculated based on established recommendations (Stebbins et al., 2006). The ankle angle of the single-segmented foot model was defined by markers on both malleoli, the calcaneus, the first, second and fifth metatarsals head. The hindfoot-tibia and ankle joints have three degrees of freedom. Knee and ankle joint centers were determined as the midpoints between the medial and lateral epicondyles and malleoli markers, respectively. The hip joint center was estimated using a previously reported regression equation (Bell et al., 1990).

The kinematic data were calculated during the landing phase: time interval between the initial contact (IC) with the force plate and peak knee flexion (PKF) (Fong et al., 2011; Orishimo et al., 2009). IC was defined as the point when the vertical ground reaction force exceeded a threshold of 10 N. Peak vertical ground reaction force (PvGRF) was defined as the maximum vertical ground reaction force value during landing. For data analysis, variables were calculated as the mean of the three successful trials of the first landing, for each direction. The dependent variables of interest were sagittal and frontal planes of the hindfoot-tibia (three-segmented foot) and ankle angles (single-segmented model); measured at IC, PvGRF, and PKF. Additionally, we calculated the joint excursions of those joints, computed as the subtraction of the angle between IC and PKF (Orishimo et al., 2009). The joint angles were reported in degrees. After conducting a residual analysis on joint kinematics to determine the optimum cut-off frequency (Winter, 2009), a 4th order low-pass Butterworth filter with a 10 Hz cut-off was employed.

2.4. Statistical analyses

Data were analyzed using SPSS (IBM, Chicago, USA). Descriptive statistics and normalcy tests were conducted. Repeated-measures analysis of variance were performed to assess differences between foot models, with each direction analyzed separately. If significant differences were attained, pairwise comparisons with a Bonferroni adjustment were conducted. Statistical significance was set *a priori* at $p < 0.05$.

3. Results

Descriptive statistics (mean and standard deviation) of the kinematic dependent variables during the lateral and forward

jump-landings to compare the three- and single-segmented foot models are presented in Table 1.

There were statistically significant differences regarding ankle kinematics of the two models. During both directions, the three-segmented foot model demonstrated lower dorsiflexion angles at PKF and PvGRF compared to the single-segmented foot (LJ and FJ, $p < 0.001$) (Fig. 1).

Additionally, the three-segmented model had lower sagittal hindfoot-tibia excursion in the lateral (41.8 ± 9.8) and forward (40.8 ± 8.6) directions than the ankle (LJ: 46.7 ± 10.6 ; FJ: 45.4 ± 10.0) of the single-segmented foot model (LJ and FJ, $p < 0.001$). Similarly, in the lateral direction the three-segmented foot also exhibited lower frontal hindfoot-tibia excursion (5.7 ± 4.4) compared to the ankle of the single model (7.1 ± 4.9) ($p < 0.05$).

4. Discussion

The complexity of the foot-ankle anatomy has a noteworthy influence on ankle's biomechanics (Brockett and Chapman, 2016). Previous studies that have investigated the lower extremity landing biomechanics have employed a single-segmented foot model (Decker et al., 2003; Orishimo et al., 2009; Orishimo et al., 2014). We aimed to investigate ankle kinematics between three- and single-segmented foot models. Our findings demonstrated that the three-segmented foot model exhibited lower hindfoot-tibia dorsiflexion during landing compared to the single-segmented ankle, in both jump-landing directions. Additionally, regardless of jump-landing directions, the three-segmented foot displayed lower hindfoot-tibia excursion in the sagittal plane; while in the frontal plane, only the lateral direction presented statistically sig-

Table 1

Descriptive table (mean \pm standard deviation) of the multi- (hindfoot-tibia) and single-segmented (ankle) foot models kinematics (angles in degrees) at initial contact, peak vertical ground reaction force and peak knee flexion, during jump-landings in lateral and forward directions.

	Initial Contact		Peak Vertical Ground Reaction Force		Peak Knee Flexion	
	Single (Ankle)	Multi (Hindfoot-tibia)	Single (Ankle)	Multi (Hindfoot-tibia)	Single (Ankle)	Multi (Hindfoot-tibia)
<i>Forward Direction:</i>						
Plantarflexion (-)	-25.3 ± 8.9	-24.7 ± 7.0	$14.6 \pm 6.1^*$	$11.0 \pm 6.5^*$	$20.0 \pm 4.1^*$	$16.1 \pm 4.8^*$
Inversion (+)	-0.08 ± 4.6	-1.6 ± 5.8	-4.8 ± 4.4	-5.2 ± 5.0	-5.7 ± 5.0	-5.2 ± 5.6
<i>Lateral Direction:</i>						
Plantarflexion (-)	-21.1 ± 9.7	-21.9 ± 8.0	$22.7 \pm 3.9^*$	$17.2 \pm 5.2^*$	$25.6 \pm 4.2^*$	$19.9 \pm 5.2^*$
Inversion (+)	3.8 ± 4.8	2.2 ± 6.3	-1.4 ± 5.7	-2.0 ± 5.5	-2.5 ± 4.9	-2.6 ± 5.0

Abbreviation:

* Statistically significant within foot models ($p < 0.05$).

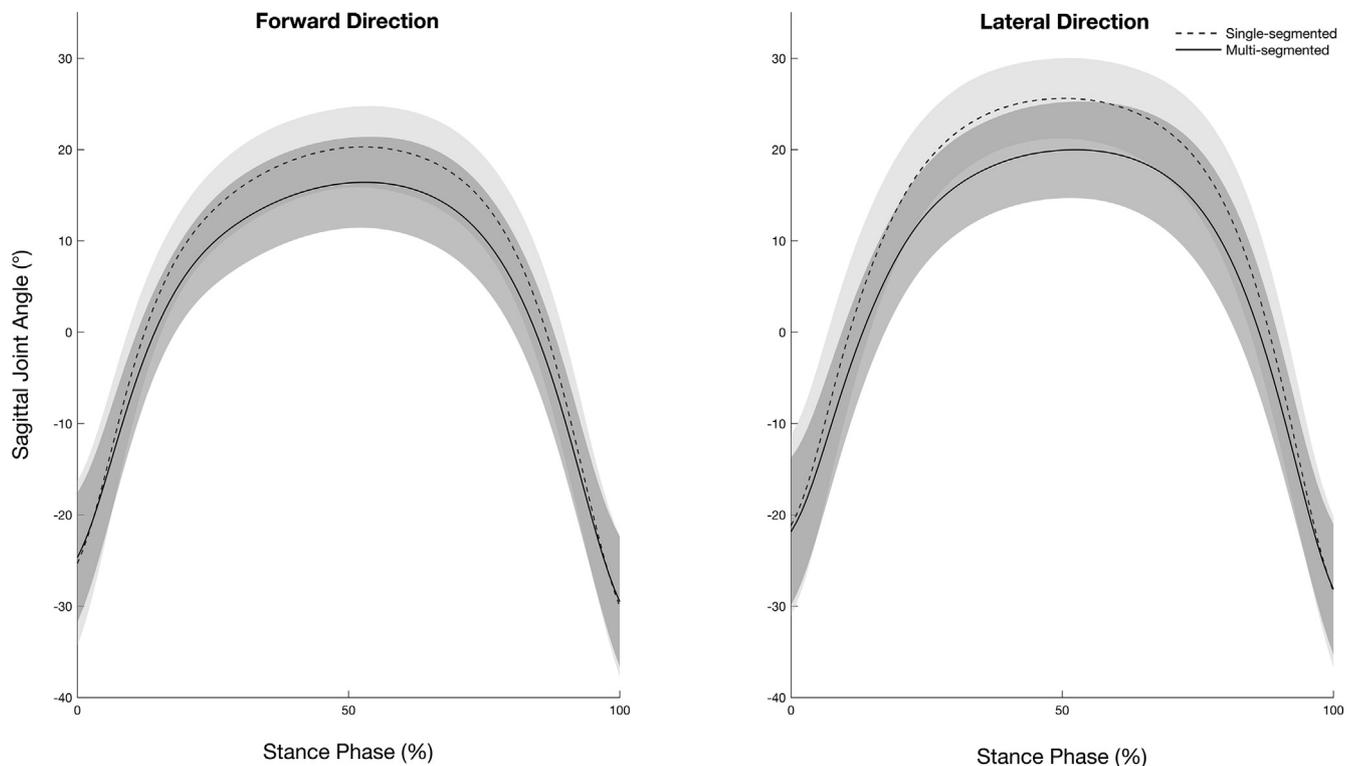


Fig. 1. Sagittal plane of the single- (represented by tibia-foot) and three-segmented (represented by tibia-hindfoot) foot models kinematics (angles in degrees), during forward and lateral jump-landing directions, from initial contact to toe off (stance phase).

nificant differences compared to the ankle excursion of the single model.

The hindfoot-tibia joint is the greatest contributor to plantar and dorsiflexion motions (Russell et al., 2011). However, this motion is not limited to that joint. The forefoot-hindfoot joint is also a contributor to the overall foot motion (De Ridder et al., 2015). Therefore, when computing the foot as a single-segment, the kinematic outputs include not only the hindfoot-tibia joint motion, but also other joints (e.g. forefoot-hindfoot) in a single-segment. Thus, the relative motion between and within the hindfoot-tibia and forefoot-hindfoot is neglected in the single-segmented foot model (De Ridder et al., 2015; Stebbins et al., 2006; Wright et al., 2016). Subsequently, the single-segmented model simplifies the foot-ankle complex leading to higher kinematic values when compared to multi-segmented foot models, as observed in our study. Previous studies also reported lower sagittal ankle kinematics in the multi-segmented foot model (De Ridder et al., 2015; Pothrat et al., 2015). For instance, in the multi-segmented foot model lower dorsiflexion excursion was found in the control (30.19°), chronic ankle instability (27.28°), and copers (28.93°) groups than the single-segmented foot model (43.05°; 37.91°; 40.46°) during side jump-landings (De Ridder et al., 2015). Additionally, during walking, the multi-segmented foot model provided lower dorsiflexion excursion (17.6°; 17.1° - normal and flat feet groups respectively), compared to the single-segmented model (25.7°; 24.6°) (Pothrat et al., 2015).

During the weightbearing acceptance of the landing phase, landing forces imposed on the body are initially attenuated by the foot-ankle complex, transferring mechanical energy throughout the lower extremity (Decker et al., 2003; Lee et al., 2018). It is suggested that the excursion of the ankle sagittal plane has less influence on kinematics at IC, but greater association with maximum angles and displacements (Hoch et al., 2015). Thus, the ankle weightbearing excursion in this plane has a substantial effect on landing biomechanics (Fong et al., 2011). The main differences observed in our study were in the sagittal plane, most likely due to being the primary plane where the ankle joint motion occurs and where the body mostly allocates impact forces attenuation (Brockett and Chapman, 2016; Fong et al., 2011; Fong Yan et al., 2014; Schmitz et al., 2007). Therefore, it is suggested to take into consideration the impact of each foot model on ankle kinematics, as it may affect the entire lower extremity kinetic chain (Pothrat et al., 2015).

In conclusion, the two foot models provided distinctive foot-ankle sagittal kinematic magnitudes. The single-segmented foot had considerably higher ankle kinematics than the multi-segmented foot. For future research, the three-segmented foot model should be considered in populations whose foot-ankle joints play a distinguishable role. It provides advanced kinematic data to better comprehend the functional abilities of the intricate foot-ankle joints.

Declaration of Competing Interest

The authors affirm there are no financial and personal relationships with other people or organizations that could inappropriately influence (bias) this work.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2019.109337>.

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