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Are foot posture and morphological deformation associated with ankle plantar flexion isokinetic strength and vertical drop jump kinetics? A principal component analysis

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ABSTRACT

Static measurements are clinically useful in characterising foot morphology, but it remains unclear to what extent it can influence dynamic lower limb performance. Therefore, the purpose of this study was to investigate if foot posture or foot morphology deformation relates to ankle plantarflexion isokinetic strength and specific kinetics variables during jumping using principal component analysis (PCA). Thirty-eight physically active participants performed drop vertical jump (DVJ) onto force platforms and ankle plantarflexion contractions in different modalities on an isokinetic dynamometer. Foot posture was assessed using the Foot Posture Index–6 item, whereas foot one-, two- and three-dimensional morphological deformation was calculated using the Arch Height Index Measurement System. A PCA was applied to the ankle plantarflexion and kinetics performance data and correlations between PCs and foot parameters measured. The analysis revealed 3 PCs within the ankle plantarflexion and DVJ kinetics variables that captured more than 80% of the variability within the data, but none of them showed significant correlations ($r \leq 0.27$) with any foot variables. While foot posture and foot morphological deformation remain of interest in characterising foot morphology across individuals, these findings highlight the lack of clinical relevance of these static evaluations at characterising lower limb and ankle performance.

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Introduction

The human foot acts as a compliant structure for energy absorption and as a rigid lever for energy generation during propulsion owing to its passive elastic and active components (Bruening et al., 2018; Holowka & Lieberman, 2018; Kelly et al., 2018). One of its key structural features is the medial longitudinal arch (MLA) which lowers and compresses for storing energy in its passive components (plantar ligaments and aponeurosis) before rising

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and shortening for releasing the stored energy during the stance phase of locomotion (Ker et al., 1987; Stearne et al., 2016). Nevertheless, the aforementioned spring-like characteristics are not uniquely passive since MLA compression also resulted in energy storage through the tendinous tissues of the intrinsic foot muscles (IFM) (Kelly et al., 2019). This mechanism allows the foot to additionally act as a damper or motor thereby removing or adding mechanical energy in steady and non-steady state locomotion (Kelly et al., 2019; Smith, G. A. Lichtwark et al., 2022) as well as decelerating and accelerating the centre of mass (COM) during jumping (Smith et al., 2021). Between all the multiple vertical jump tests, the drop vertical jump (DVJ) enables a more effective utilisation of the stretch-shortening cycle particularly in the triceps surae (Bobbett et al., 1987; Bosco et al., 1982) and so appears advantageous for stimulating the function of the foot's arch spring.

In parallel to its involvement in mechanical energy conservation, the foot plays an important role in propulsion as foot stiffness enables the ankle plantar flexors to generate large plantar flexion moments and propulsive power (Takahashi et al., 2016). The mid- and longitudinal foot stiffnesses, mainly controlled by the MLA and transversal tarsal arch (TTA), are of particular interest since they both prevent foot deformation while optimising foot propulsive work (Venkadesan et al., 2020). Measuring midfoot stiffness is therefore important but remains a challenging aspect in non-laboratory settings. To overcome this, several composite measures of foot morphological deformation have been proposed as indirect measures of foot arches passive stiffness. This includes clinical composite measures of foot one-dimensional morphological deformation 'Navicular Drop', (ND) (Brody, 1982), 'Arch Height Flexibility' (AHF) (R. A. Zifchock et al., 2017) or two-dimensional 'Foot Mobility Magnitude' (FMM) (McPoil et al., 2009) or three-dimensional 'Quarter-Ellipsoid Foot' (QEF) (Fraser & Hertel, 2021).

Using the AHF, previous studies reported that individuals with a stiffer MLA displayed greater vertical ground reaction force (GRF) magnitude and impulses, forefoot plantar pressure during walking and running (Cen et al., 2020; Williams et al., 2014; R. Zifchock et al., 2019) as well as greater vertical stiffness during jumping (Grozier et al., 2021). Additionally, Snook highlighted that participants with a flexible MLA measured by the ND presented a reduction of isokinetic ankle plantarflexion peak torque (Snook, 2001). However, if these measurements are clinically useful in characterising foot morphology across loading conditions, it is not clear to what extent it is associated with lower limb kinetics and ankle plantarflexion isokinetic strength as the aforementioned studies used a between-group difference analysis. In addition to the necessity of using a different statistical analysis, there is a need to include the FMM and the QEF measurement in the analysis since the foot deformation encompasses three-dimensional morphological changes during dynamic tasks (Fraser & Hertel, 2021).

Therefore, the aim of the study was to understand the relationships between foot posture, foot one-, two- and three-dimensional morphological deformation, ankle plantarflexion isokinetic strength and DVJ kinetics using a Principal Component Analysis (PCA). It was hypothesised that foot three-dimensional morphological deformation would be moderately associated with ankle plantarflexion isokinetic strength and DVJ kinetics whereas one- and two-dimensional morphological deformation as well as foot posture would not.

Materials and methods

Design

This study was an exploratory biomechanical analysis with a cross-sectional design in which ankle plantarflexion isokinetic strength, vertical drop jump kinetics and foot parameters were captured during one testing session. A session was used one week before the testing session in order to familiarise participants with the different tasks and registered each individual isokinetic setting parameters. Participants were asked to avoid strenuous exercises for 48 hours before testing to prevent any fatigue and/or delayed onset muscle soreness that could interfere with the performance.

Participants

Thirty-eight healthy active individuals (18 males, 20 females; mean age 21.5 ± 4.8 years; BMI 23.5 ± 2.9 kg/m²) participated in this study. They were included if they met the following criteria: (1) age between 18 and 45 years and (2) active in some form of physical activity for at least 30 minutes per day, at least three times a week. Exclusion criteria were: (1) score of Foot Ankle Ability Measure of daily living and sport <100%, (2) history of foot and ankle sprain or pain in the past 6 months, (3) leg or foot fracture in the previous year, severe foot deformity, (4) previous foot strengthening experience in the past 6 months for at least 2 weeks and more than one session per week. Participants demographic information, foot posture and morphological deformation on the dominant limb are detailed in [Table 1](#). All patients gave written informed consent for their participation and the study protocol was *a priori* approved by the local Swiss ethical committee (#2021–01339).

Table 1. Participant demographics and dominant foot posture and morphological deformation measures.

	Male (n=18)	Female (n=20)
	N(%)	N(%)
	Mean $\pm$ SD	Mean $\pm$ SD
Age (years)	29.6 $\pm$ 5.1	29.2 $\pm$ 5.0
Height (cm)	173.2 $\pm$ 9.0	172.8 $\pm$ 8.8
Mass (kg)	68.9 $\pm$ 13.8	68.6 $\pm$ 13.2
BMI (kg/m ²)	23.9 $\pm$ 3.1	21.9 $\pm$ 2.0
Level of Physical Activity (AU)	33.1 $\pm$ 42.1	32.2 $\pm$ 40.0
Dominance		
Right	17 (94.4%)	18 (90.0%)
Left	1 (5.6%)	2 (10.0%)
FPI score	3.6 $\pm$ 3.1	3.4 $\pm$ 3.3
FPI group		
Highly Pronated	0 (0.0%)	2 (10.0%)
Pronated	4 (22.2%)	5 (25.0%)
Normal/Neutral	12 (66.7%)	12 (60.0%)
Supinated	2 (11.1%)	1 (5.0%)
Highly Supinated	0 (0.0%)	0 (0.0%)
Navicular Drop (mm)	6.9 $\pm$ 3.0	7.0 $\pm$ 3.4
Arch Height Flexibility (mm/kN)	7.7 $\pm$ 2.4	8.1 $\pm$ 4.4
Foot Mobility Magnitude (cm)	0.6 $\pm$ 0.2	0.6 $\pm$ 0.2
Quarter Ellipsoid Foot		
Δ Surface Area (cm ²)	−0.3 $\pm$ 6.5	−0.6 $\pm$ 6.6
Δ Volume (cm ³)	−21.1 $\pm$ 28.8	−22.5 $\pm$ 29.7
Δ Surface Area to Volume Ratio (%)	0.8 $\pm$ 0.5	0.9 $\pm$ 0.7

BMI, Body Mass Index; FPI, Foot Posture Index; AU, arbitrary units; Δ , Delta.

Procedures

At the beginning of the testing session, limb dominance was determined using a cluster of three unskilled tasks (gait initiation, stepping down, kicking a ball) and three skilled tasks (picking up a marble with toes, tracing shapes with foot, stamping out a simulated fire) (Schneiders et al., 2010). Each task was performed with each leg and preference (right, left, none) was summed for determining limb dominance at the end of the cluster. The participants' average current level of physical activity was assessed and calculated through a custom questionnaire based on the Godin Leisure-Time Exercise (Godin & Shephard, 1997).

Foot posture and foot morphological deformation

Foot posture was assessed in relaxed bipedal standing position using the Foot Posture Index-6 item version (FPI-6) (Redmond et al., 2006). This tool is a multisegmental clinical quantification tool to assess static foot alignment in all three planes in order to classify foot posture types (Redmond et al., 2006). FPI-6 has a good internal concurrent validity (Redmond et al., 2006) and it is known to possess good to excellent inter- and intra-rater reliability with different experience level (Evans et al., 2012; Morrison & Ferrari, 2009; Terada et al., 2014). For each of the six observational criteria we gave a 5-point scale that ranges from -2 to +2, with negative numbers indicating a more supinated foot posture and positive numbers indicating a more pronated foot posture. Finally, the final composite score of the FPI-6 permitted classification of the posture of the dominant foot of each participant as highly pronated, pronated, normal/neutral, supinated or highly supinated based on previous cut-off (Redmond et al., 2006).

Foot morphological deformation was assessed using the Arch Height Index Measurement System (AHIMS) (JAKTOOL Corporation, Cranberry, NJ) which has been shown to have an excellent intra- and inter-rater reliability at measuring foot length, foot width, truncated foot length and dorsal arch height (Butler et al., 2008). As previously mentioned, foot morphological deformation measures are based on the amount of deformation between an unloaded position and a loaded position. For the unloaded position, participants were seated on an adjustable chair with their dominant foot resting on the floor with an estimated weight of 10% of body weight (BW) (Dempster & Gaughran, 1967). For the loaded position, participants were asked to stand and place approximately 95% of their entire BW on their dominant foot, while the other foot rested lightly on the floor. Before the testing session, participants were familiarised with each bodyweight threshold by using a force platform (ForceDesks FD4000 Dual Force Platforms, Vald Performance, Brisbane, Queensland, Australia). This method differs from all the previous studies using a bipedal standing position (50% of BW). Since the IFM shows little to no activity during double-limb upright standing (Basmajian & Stecko, 1963; Mann & Inman, 1964) but are active during single-limb upright standing (Kelly et al., 2012; Ridge et al., 2022) using a 'quasi' single leg stance position in the loading condition allows a greater activity of the IFM, which increases their contribution in controlling foot arches deformation.

Foot one-dimensional morphological deformation was calculated by the AHF (R. A. Zifchock et al., 2017) using the following equation:

$$\text{AHF (mm/kN)} = \frac{h_{\text{sitting}} - h_{\text{standing}}}{0.85 \times \text{BW}} \times \frac{10000}{9.81} \quad (1)$$

where h is the dorsal arch height (measured in centimetres) at half of the foot length and the 0.85 coefficient assuming an 85% change in load from the sitting position (10% BW) to the standing position (95% BW).

A second measure of one-dimension deformation was assessed using the ND (Cote et al., 2005) calculated using the following equation:

$$\text{ND (cm)} = \text{NH}_{\text{sitting}} - \text{NH}_{\text{standing}} \quad (2)$$

where NH is the navicular height (in centimetres) measured by a manual caliper (resolution : 0.02 mm).

Foot two-dimensional morphological deformation was calculated by the FMM (McPoil et al., 2009) using the following equation:

$$\text{FMM (cm)} = \sqrt{(h_{\text{sitting}} - h_{\text{standing}})^2 + (w_{\text{sitting}} - w_{\text{standing}})^2} \quad (3)$$

where h is the dorsal arch height at half of the foot length and w is the foot width (all measured in centimetres).

Finally, foot three-dimensional morphological deformation was calculated by the QEF developed by Fraser et al. (Fraser & Hertel, 2021). This evaluation consists of measuring the surface area (SA) of deformation characterising the widening and lengthening of the foot during loading using the following equation:

$$\text{SA (cm}^2\text{)} = \pi \left[0.3333 \left((0.5.l.w)^{1.6075} + (0.5.l.h) + (w.h)^{1.6075} \right) \right]^{0.6221} \quad (4)$$

$$\Delta \text{SA} = \text{SA}_{\text{sitting}} - \text{SA}_{\text{standing}}$$

where l = total foot length, w = foot width and h = dorsal arch height (measured in centimetres).

The volume (V) of deformation characterising the deformation of the MLA and TTA during loading using the following equation:

$$V (\text{cm}^3) = 1.0467 (0.5.l.w.h) \quad (5)$$

$$\Delta V = V_{\text{sitting}} - V_{\text{standing}}$$

The surface area-to-volume ratio (SA:V) characterising the change in both widening and lengthening in relation to foot arches deformation using the following equation:

$$\Delta \text{SA:V (\%)} = (\text{SA:V}_{\text{standing}} - \text{SA:V}_{\text{sitting}}) \times 100 \quad (6)$$

Drop vertical jump kinetics

Before performing the double-leg DVJ task, participants undertook a standardised warm-up consisting of 2 minutes of jogging, 5 lateral, forward and backward lunges per side, 5 deep squats, 10 double-leg pogo jumps in place, 10 double-leg forward, backward hops and 10 jump lunges per side. After the warm-up, participants were given 5 familiarisation trials to practice the double-leg DVJ task

at maximal effort. A box height of 30 cm adjacent from two force platforms (ForceDecks FD4000 Dual Force Platforms, Vald Performance, Brisbane, Queensland, Australia) was used to complete the bilateral DVJ. Before each DVJ trial, the force platforms were zeroed to reduce the signal noise. Participants were instructed to keep their hands placed on iliac crests, to drop off the box, land on the plates with both feet at the same time and rebound off the force platform as quickly as possible aiming for maximum jumping height. They were then instructed to land softly remaining completely still on the platforms for 2–3 seconds. Verbal instructions to maintain knee and hip extension during flight time were also given. When the previous instructions were not followed, trials were deemed invalid and participants were asked to repeat. Participants completed three successful trials and the mean of three successful trials were used in the final analysis. In order to increase the external validity of the study while not altering performance, every participant jumped with standardised shoes presenting a minimalist index of 95% (Esculier et al., 2015).

Raw data of the vertical GRF from the force platforms was recorded at 1000 Hz and analysed using the commercially available software (ForceDecks, Vald Performance Pty Ltd., Brisbane, Australia) with a 20 N threshold used to delineate the start and the end of the ground contact and the end of the flight phase. Eccentric phase of the DVJ was identified as the time from the start of the ground contact until the vertical velocity of the centre of mass reached 0 m/s. The concentric phase was identified as the time from the end of the eccentric phase until the instant of take-off. Variables of interests calculated from the vertical GRF by the manufacturer software can be found in Table 2. and were classified as performance variables performed by the work of both feet and foot dominant kinetics variables.

Table 2. Variables of interest for the drop vertical jump and the ankle plantarflexion isokinetic strength tests.

Drop Vertical Jump (Performance variables)

Jump height (cm)
Peak power (W)
RSI mod (m/s)
Vertical velocity at take-off (m/s)
Contact time (s)
Flight time (s)

Drop Vertical Jump (Foot dominant variables)

Eccentric vertical mean force (N)
Concentric vertical mean force (N)
Eccentric vertical impulse (N.s)
Concentric vertical impulse (N.s)
Vertical active stiffness (N/m)
Vertical passive stiffness (N/m)
Drop landing RFD (N/s)
Vertical mean eccentric/concentric force ratio (%)

Ankle Plantarflexion Isokinetic Strength

Maximal isometric torque (Nm)
Concentric peak torque at 30°/s (Nm)
Mean endurance peak torque (Nm)
Maximal total work (J)
Fatigue index (%)

RSI mod, Reactive Strength Index modified; RFD, Rate of Force Development.

Ankle plantarflexion isokinetic strength

Ankle plantarflexion isokinetic strength was assessed after the DVJ task using an isokinetic dynamometer (Biodex Medical Systems Inc, Shirley, NY). Three testing modalities were used to assess three different neuro-muscular capacities of the plantar flexors: maximal isometric voluntary torque (MIVT), maximal concentric peak torque, and endurance strength. In the three testing methods, participants were in supine position with the hip in 0° of extension and the knee between 0° and 10° of flexion (Snook, 2001). Their foot was strapped to a pedal with the centre of axis of rotation aligned with the medial malleolus and a correction for gravity was applied.

In the first test measuring MIVT with ankle at 0°, participants were asked to perform 6 submaximal contractions from 50% to 90% of their self-perceived MIVT on the isometric mode of the dynamometer. Then participants were required to perform three maximal isometric voluntary contractions during 5 seconds separated by a minimum of 40 seconds of rest. Data was collected at 100 Hz and analysed using a customised Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, USA, [2016 version]). The highest torque (expressed in Nm) was considered as the MIVT and was calculated using the difference between the mean of a 100 ms window around the peak (50 ms before and after) and one at baseline of the torque-time curve (Tourillon et al., 2022). For the second test, the dynamometer was switched to the isokinetic mode. Five submaximal contractions at 30°/s were given before participants were instructed to perform 4 maximal plantarflexion contractions at 30°/s in a range of motion between 20° of plantarflexion and 10° of dorsiflexion. Maximal peak torque was calculated as the highest peak torque over the four contractions and was expressed in Nm.

The third test assessed endurance strength of the plantarflexors using a previously studied isokinetic fatigue protocol (Fouchet et al., 2012). Participants were required to perform 30 consecutive maximal ankle plantarflexion contractions at an angular velocity of 30°/s (120°/s of return) in the same range of motion as the previous test. Peak torque and total work were calculated for each repetition of the 30 contractions. Three methods of calculation were used to assess endurance strength with 1) the mean endurance peak torque (Nm) representing the sum of the peak torque of each contraction, 2) the total work (J) representing the sum of the work of each contraction and 3) the fatigue index (%) representing the difference between the mean peak torque of the last three repetitions over the mean peak torque of the first three repetitions. These three methods of analysis were chosen as they have shown to possess higher reliability in comparison to other methods (Bosquet et al., 2010; Porter et al., 2002).

Statistical analysis

The statistical analysis comprised a Principal Component Analysis (PCA) and a common correlation analysis between illustrative variables and the identified principal components (PCs). This method consists of analysing a selection of discrete points that allows biomechanical variables to be merged by patterns of common variation and to assess their linear relationship. Before applying the PCA, variables were centred (subtraction of mean), normalised (division of SD) and reduced (Husson et al., 2010). PCA was then applied to the data from the DVJ and isokinetic performance tests using R software (R Foundation for Statistical Computing) with the Factominer package. Foot posture and morphological

deformation data were considered as illustrative variables. To understand the relationship between the identified PCs and the illustrative variables, a Pearson product-moment correlation with an alpha-level of 0.05 was adopted. Correlation coefficients were interpreted as follows (small = 0.1, moderate = 0.3, and large = 0.5) (Hopkins et al., 2009).

Results

Eighteen PCs were identified within the vertical drop jump and the ankle plantarflexion isokinetic strength tests, which captured 99% of the variability within the data. Of these PCs, three captured approximately 80% of the variability within the data (PC1: 45.5%; PC2: 21.8%; PC3: 12.2%). More than 75% of the contribution was created by 8 variables ($r > 0.70$) for PC1 including both power, reactive strength and stiffness capacities during the DVJ (Table 3). For the PC2 more than 75% of the contribution was created by 7 variables ($r > 0.50$) including jump height drivers variables (concentric impulse, take-off velocity, flight time) as well as ankle plantarflexion isokinetic strength variables (Table 3). For the PC3, more than 75% of the contribution was created by 5 out of 7 variables ($r > 0.37$) from PC2 so demonstrating redundancy. These three PCs showed moderate ($r = 0.37$; PC1), large ($r = 0.51$; PC3) and very large correlation ($r = 0.73$; PC2)

Table 3. Principal components and their relationship with foot posture and foot morphological deformation.

Principal Component 1 (PC1)			Foot Posture and Foot Morphological Deformation	
Variables	contri. (%)	r value	Variables	r value with PC1
RSI mod	11.77	0.98*	Foot posture index	−0.06
Concentric vertical mean force	11.42	0.97*	Navicular drop	0.25
Peak power	11.34	0.96*	Arch height flexibility	0.20
Active stiffness	11.08	0.95*	Foot mobility magnitude	0.20
Passive stiffness	10.28	0.92*	QEF Δ surface area	−0.08
Eccentric vertical mean force	8.89	0.85*	QEF Δ volume	−0.14
Contact time	7.90	−0.80*	QEF Δ surface area/volume ratio	0.12
Drop landing RFD	6.19	0.71*		
Principal Component 2 (PC2)			Foot Posture and Foot Morphological Deformation	
Variables	contri. (%)	r value	Variables	r value with PC2
Concentric vertical impulse	16.62	0.81*	Foot posture index	0.04
Vertical velocity at take-off	13.84	0.74*	Navicular drop	0.18
Flight time	13.76	0.74*	Arch height flexibility	−0.24
Mean endurance peak torque	9.41	0.61*	Foot mobility magnitude	−0.10
Maximal total work	8.31	0.57*	QEF Δ surface area	−0.07
Maximal isometric torque	7.19	0.53*	QEF Δ volume	−0.04
Concentric peak torque at 30°/s	6.80	0.52*	QEF Δ surface area/volume ratio	−0.24
Principal Component 3 (PC3)			Foot Posture and Foot Morphological Deformation	
Variables	contri. (%)	r value	Variables	r value with PC3
Maximal total work	15.36	−0.58*	Foot posture index	−0.04
Flight time	11.54	0.50*	Navicular drop	0.19
Vertical velocity at take-off	11.42	0.50*	Arch height flexibility	0.01
Mean endurance peak torque	10.96	−0.49*	Foot mobility magnitude	0.07
Eccentric impulse	9.74	0.46*	QEF Δ surface area	−0.25
Drop landing RFD	9.70	0.46*	QEF Δ volume	−0.27
Concentric impulse	6.86	0.39*	QEF Δ surface area/volume ratio	0.12
Maximal isometric torque	6.15	−0.37*		

RFD, Rate of Force Development; QEF, Quarter Foot Ellipsoid; RSI mod, Reactive Strength Index modified.

contri.: represents the contribution (in percentage) of each variable to the principal components.

* $p < 0.05$.

with DVJ height demonstrating different performance strategies even if the verbal cue was the same for every participant. Finally, we observed that none of these three identified PCs within the DVJ and ankle plantarflexion isokinetic strength data presented significant association with foot posture of foot morphological deformation parameters ($r \leq 0.27$; $p > 0.05$) (Table 3).

Discussion

The aim of this study was to determine if there was a relationship between foot posture, foot one-, two- and three-dimensional morphological deformation, ankle plantarflexion isokinetic strength and DVJ kinetics. A further objective was to determine if foot three-dimensional morphological deformation presented a stronger relationship in comparison to foot posture and foot one-, two-dimensional morphological deformation. The primary finding was that none of the foot variables (posture, deformation) were significantly associated with the identified PCs. Another important and novel finding was that foot three-dimensional morphological deformation was not more associated with ankle plantarflexion isokinetic strength or DVJ kinetics not supporting our hypothesis.

The main result of this study does not comply with previous studies stating that MLA flexibility measured by the ND and the AHF influences GRF characteristics during various dynamic tasks (Cen et al., 2020; Grozier et al., 2021; Sudhakar et al., 2018; Williams et al., 2014; R. Zifchock et al., 2019). The previous studies used a between-group analysis but did not clarify the relationship between foot arch flexibility and GRF kinetics. By using a PCA in this study, we demonstrated that foot one-dimensional morphological deformation displays a weak association with force absorption and generation of the lower limb during a DVJ. This is in contradiction with the study of Grozier et al. showing that individuals with a stiffer MLA defined by a low AHF displayed greater active vertical stiffness during DVJ (Grozier et al., 2021). In our study, AHF was poorly associated with active stiffness ($r = 0.19$) meaning that having a stiffer foot arch is not strongly associated with having an increase of vertical stiffness during a DVJ. More surprisingly, adding clinical composite measures of foot two- and three-dimensional morphological deformation in the analysis did not increase the relationship. Indeed, even foot deformation encompasses three-dimensional morphological changes during DVJ for dissipating and generating energy (Smith et al., 2021), the FMM and QEF parameters presented zero to weak association ($r \leq 0.27$; $p > 0.05$) with the identified PCs. These results highlighted that even if the measurements (FPI, ND, AHF, FMM, QEF) are clinically useful in characterising foot morphology across loading conditions, they are still derived from two static positions and may not specifically translate to dynamic foot function as previously studies mentioned (Behling & Nigg, 2020; Paterson et al., 2015). Therefore, even if these parameters can be measured quickly and accurately with low-cost instrumentation, caution is needed to use them on their own to explain the role of the foot arches flexibility at influencing GRF characteristics during DVJ.

The secondary results of this study are in disagreement with a previous study that has shown that participants with a flexible MLA measured by the ND presented a reduction of isokinetic plantarflexion peak torque (Snook, 2001). The rationale behind these results was that the midfoot of the flexible group remains ‘unlocked’ and therefore generates less ankle plantarflexion torque (Snook, 2001). However, our study highlighted that actual clinical foot

arches passive stiffness measurements are not significantly associated with any ankle plantar-flexion isokinetic variables. Although the significance of a stiff midfoot has been demonstrated to help to efficiently transfer the mechanical power generated by the ankle during push-off (Takahashi et al., 2016), these measurements (ND, AHF, FMM, QEF) may probably not be enough to completely explain the regulation of foot stiffness. Indeed, previous studies demonstrated the relevance to consider other factors such as the potential of foot muscles to actively regulate the arch stiffness (Kelly et al., 2015, 2019). As such, the extrinsic foot muscles (EFM) are the dominant MLA stabilisers in the foot complex (Farris et al., 2019; Maharaj et al., 2017), whereas the IFM is more prone to provide forefoot stiffness during propulsion enhancing the ankle joint torque production by controlling the leverage of the foot (Farris et al., 2020; Smith et al., 2021; Smith, G. Lichtwark et al., 2022). Taken together, these studies highlighted the importance of the EFM in combination with IFM and viscoelastic structures at regulating foot stiffness during ballistic tasks. This may explain the results of Yamauchi et al. who showed that toe flexors strength was associated with vertical jump performance (jump height, peak power, reactive strength) and GRF vertical impulse whereas arch height was not (Yamauchi & Koyama, 2020). Hence, relying on foot muscle strength seems an important parameter to consider when assessing the influence of human foot stiffness on ankle plantarflexors force transfer. However, further studies are warranted to clarify the relationship between foot active stiffness and ankle plantarflexion isokinetic strength.

A last finding of our study relates to the variables participating in PC1 and PC2 construction. PC1 is being composed of variables related to power (peak power), reactive strength (RSI mode) and stiffness capacities (active and passive stiffness, drop landing RFD) during DVJ. Thus, it represents a greater ability to use the stretch-shortening cycle by rapidly moving from an eccentric to a concentric action in a short contact time. This ability enables a greater amount of energy to be stored and returned through the contractile and elastic tendinous tissue of the lower limb allowing supramaximal power outputs (Bosco et al., 1982; Farris et al., 2016; Lichtwark et al., 2007). However, even if the foot-ankle joint is a key site of power release in jumping (Bobbert, 2001) our study demonstrated that this stretch-shortening cycle ability is not associated with foot posture and foot morphological deformation. In addition, variables from PC2 are both composed of ankle plantarflexion isokinetic strength outcomes and DVJ kinetics parameters (concentric vertical impulse, vertical velocity at take-off and flight time). This relationship between kinetic variables could be explained thanks to forward dynamics (Linthorne, 2001) as a high concentric impulse is the resultant of high force generated in triple extension of the lower limb. This impulse allows a high vertical velocity at take-off, which then dictates flight time. Therefore, our results highlighted that ankle plantar flexors isokinetic strength enables high propulsive force to be generated during DVJ. This is in accordance with previous studies showing that ankle plantar flexors play a critical role in accelerating the body rapidly during ballistic tasks (Marshall et al., 2014; Pandey et al., 2021; Vanezis & Lees, 2005). Interestingly, it has been demonstrated that a nerve block aiming at deleting the active contribution of the IFM affected ankle plantarflexion mechanics (Farris et al., 2019; Kessler et al., 2020; Smith, G. Lichtwark, et al., 2022). This functional coupling between IFM activity and ankle function could explain the improvement in performance during vertical jump (Kokkonen et al., 1988; Unger & Wooden, 2000) and horizontal jump (Goldmann et al., 2013; Hashimoto & Sakuraba, 2014) after a foot strengthening protocol. Thus, our results associated with previous studies highlighted a greater relationship between ankle

plantarflexors, foot muscles strength (IFM & EFM) and jumping performance kinetics in comparison to foot posture and foot morphological deformation individually.

The present study had several limitations. First, we demonstrated no associations between foot deformation and ankle plantarflexion peak torque during an analytic isokinetic task, which does not exclude that ankle plantarflexion moment and power could be associated with foot deformation during the propulsion phase of a functional task like the DVJ. Additionally, the sample size of participants included in the study was heterogeneous regarding the level of physical activity (Table 1) and the type of sport practice, which may have generated varied performance strategies during jumping and masked certain potential associations. Finally, we evaluated kinetics on the dominant foot during a bilateral DVJ task instead of a unilateral one which could have changed the results of the study. This choice was made because of the study sample. Indeed, unilateral DVJ has been shown to expose the limb to significantly greater GRF (Maloney et al., 2018). This higher intensity task involves a level of technique, strength and timing that only experienced athletes would be able to achieve, which was not the majority typology of our sample

Conclusion

The results demonstrated that foot posture and foot morphological deformation were not associated with DVJ kinetics nor plantar flexion performance during isokinetic tests. While these functions could be measured quickly and accurately with low-cost instrumentation, these findings highlight the lack of clinical relevance of these static and passive evaluations at influencing ankle plantarflexion isokinetic strength and lower limb force absorption and generation during jumping. Further studies are warranted to focus on the validation of specific dynamic foot measures (e.g. active stiffness, strength) in order to help clinicians understand the role of the human foot in enhancing lower limb performance during ballistic tasks.

Protocol registration

The research presented in this study was conducted at La Tour Hospital and the study protocol was a priori approved by the local Swiss ethical committee (#2021-01339).

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