Influence of metatarsophalangeal joint stiffness on take-off performances and lower-limb biomechanics in jump manoeuvres

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Running Title: MTPJ stiffness in countermovement jumps

Abstract

Forefoot and toes are prominent regions for locomotion and individual metatarsophalangeal joint (MTPJ) stiffness may be linked to jump take-off mechanics and performances. However, little is known about the relationships between MTPJ stiffness and take-off related variables. This study examined the relationship between individual MTPJ stiffness and biomechanical variables under various vertical countermovement jumps (CMJ) conditions. We measured MTPJ stiffness on twenty-one male university basketball players and then asked them to perform jumps under single, consecutive, and running CMJ conditions. Pearson's correlation coefficient was employed to examine the relationships between MTP passive stiffness and each jumping performance, ground reaction force (GRF), and joint kinematic and kinetic variables. The results indicated that MTPJ stiffness significantly correlated with maximum jump height (r=0.49, *moderate*), peak take-off velocity (r=0.47, *moderate*), peak take-off ankle plantarflexion moment (r=0.68, *strong*), peak dorsiflexion moment (r=0.60, *strong*), and peak take-off ankle power (r=0.44, *moderate*) in consecutive CMJ. Only a moderate correlation between MTPJ stiffness and peak MTPJ extension take-off velocity (r=-0.46, *moderate*) was determined in a single CMJ. There were no significant correlations found in running CMJ conditions. These findings imply that higher MTPJ stiffness of participants was related to improved jump performances in consecutive jumps.

Keywords*:* Jumping, toe stiffness, basketball, countermovement jump

Word Count: 197 (Abstract), 3883 (Main text)

Introduction

In competitive sports involving rebounds, blocks or shots from the ground, jumping is an essential skill (Pau & Ciuti, 2013; Wissel, 2012). The ability to jump can differentiate elite players from sub-elite players (Ziv & Lidor, 2010). Most jumping studies have predominantly reported on hip, knee, and ankle joint data (Leppanen et al., 2017; Zhang et al., 2005), with little consideration for the metatarsophalangeal joint (MTPJ). The MTPJ connects metatarsal bones and proximal phalanges of the toes to allow effective push against the ground during propulsion/take-off (Alexander et al., 1987; Zelik et al., 2015). The epidemiological mechanism for the causal effect associating jump tasks with the MTPJ remains poorly understood. During game situations and training sessions, high levels of ground reaction forces are exerted on the foot and transferred through the MTPJ because of repeated jump take-off strategies, which consequently may alter the mobility of the MTPJ and foot function. Therefore, in relation to basketball, understanding the use of MTPJ for jump take-off strategies will provide an insight into the level of flexibility (or passive stiffness) of the MTPJ.

Forefoot and toes are suggested to be prominent regions for human locomotion (Rolian et al., 2009), as MTPJ stiffness is related to lower-limb stiffness (Liu et al., 2020), running economy (Man, Lam et al., 2016) and injury potential (Senda et al., 1999). Additionally, forefoot biomechanics can provide information to assess athletic performance and training regimes in basketball, as observed by higher forefoot plantar pressure recorded in the stop-jump shot and lay-up in female basketball players (Pau & Ciuti, 2013). The information of forefoot loading and GRF would help to understand how the forces are transferred through the MTPJ to the proximal joints during jumping take-off.

When performing a jump, an athlete induces rapid muscle stretching followed by concentric contraction. Pre-stretching the foot plantar muscles can improve jumping performance. While the forefoot generates force by pushing against the ground to provide propulsion during take-off, increase of toe flexor strength (as reflected by higher MTPJ stiffness) leads to better long jump performance (Goldman et al. 2013; Man et al., 2016b; Morita et al., 2015). Increased MTPJ stiffness may tighten the foot intrinsic muscles ligament and plantar fascia and thus increase leg stiffness (Frank et al., 2000; Larkins & Snabb, 1999; Salinero et al., 2014). Larger leg stiffness is associated with better take-off velocity and jump height (Struzik & Zawadzki, 2013), as indicated by the higher GRF generated. Stefanyshyn and Nigg observed university basketball players and long jumpers perform running vertical jumps and running long jumps, respectively. Their sagittal plane analysis indicated that the MTPJ was responsible for 16% of the energy absorption but it did not contribute to energy generation (Stefanyshyn & Nigg, 1998). As very little or no energy at MTPJ is generated during push/take-off, athletes wearing shoes with increased bending stiffness (i.e. limited human MTPJ motion) can reduce energy dissipation at the MTPJ and enhance jumping performance. Inconsistent jump height performances were reported across previous studies (Stefanyshyn & Nigg, 1998; Lam et al., 2017). This might be due to the individual forefoot structures or stiffness such that heavier/taller participants do not necessarily require shoes with higher bending stiffness than the lighter/smaller participants (Stefanyshyn & Fusco, 2004). Furthermore, another study (Liu et al., 2020) found distinct MTPJ stiffness among basketball players, runners and other athletes, which implies that MTPJ stiffness could be related to types of sport participations and that individual athletes may optimize their MTPJ to achieve various type of movements. However, studying how individual MTPJ stiffness would relate to jumping performance would require further investigation.

Theoretically, different types of jumps (e.g. single standing jump, consecutive standing jump and running jump) would exhibit distinct jump techniques and coordination, which may require MTPJ utilizations across jump types (Cormack et al., 2008; Miura et al., 2010; Lam et al., 2020). While the single standing countermovement jump is predominantly used to assess differences between various interventions, consecutive jumps of which participants perform a quick second jump for a rebound/attack is the key to success in all competitive sports involving rebounds, blocks or shots from the ground (Wissel, 2012). Consecutive movements induce different lower-limb kinematics and loading compared with single movements (Cormack et al., 2008; Lam et al., 2020). On the other hand, the running jump is a common technique used for attacking and/or rebounding skills (Miura et al., 2010). Unlike standing jumps, participants experience higher horizontal forward inertia and larger roll-over excursion at MTPJ prior to the take-off during a running jump than a single standing jump. This demonstrates distinct lower limb mechanics and knee extension moments (Sell et al., 2005). The changes in knee extension moment is associated with the proximal tibial forward shear forces in planned and reactive jump tasks (toward three different directions), with larger knee extension moments in the lateral and reactive jumps than preplanned jumps (Sell et al., 2005). However, these studies did not examine changes in forefoot biomechanics and MTPJ stiffness that denotes the mechanical characteristics of the forefoot. This may influence the muscle mechanics of the intrinsic foot muscle as well as proximal joint stiffness (Frank et al., 2000; Larkins & Snabb, 1999; Salinero et al., 2014). In relation to the fact that no energy is generated at MTPJ during take-off (Stefanyshyn et al., 2016), the differences in forefoot rolling mechanics (angle, velocity and loading) among static, consecutive and running jumps could result in distinct adaption of the individual MTPJ.

To date, passive MTPJ stiffness of a human foot can be reliably measured with a computer-controlled dynamometer (Man, Leung, et al., 2016) and used to predict running performance (Man, Lam, et al., 2016). To the best of our knowledge, how individual MTPJ stiffness would relate to jumping and take-off biomechanics is lacking. Hence, the purpose of this study was to examine the relationships between passive MTPJ stiffness and the ground reaction force (GRF) and movement mechanics that are related to take-off performances in different types of countermovement jumps (single standing, consecutive standing and running jumps). Based on previous literature, it is expected that higher MTPJ stiffness would lead to increased jump height and take-off velocity. It is also expected that MTPJ stiffness would relate more to MTPJ variables than other proximal joint variables. The findings from this study can be used as reference information for talent identification and footwear selection with different forefoot bending stiffnesses.

Methods

Participants

A minimum of 21 participants was determined in G-Power software with an alpha of 0.05 and power of 0.8, as specific in our pilot data. Therefore, twenty-one male university basketball players [age = 21.1 (2.1) years; height = 1.80 (0.04) m; mass = 71.0 (7.5) kg; playing experience = 5.2 (1.9) years] participated in this study. All participants were students in a local sports university, and they were experienced with the three test jumps. All participants were right-leg dominant and free of lower extremity injuries for six months prior to the study. Only participants with a foot length of US size 9.0 (0.5) for both feet were recruited, as determined using a standard foot measuring device (Brannock Device, Syracuse, NY, USA). Experimental procedures were approved by the institutional review board (IRB-2018-BM-010) and a signed consent form from each participant was obtained prior to data acquisition.

Passive MTPJ stiffness measurement

Passive MTPJ torque denoted mechanical characteristics and stiffness of the forefoot (Man, Lam, et al., 2016). The MTPJ passive torque of the right foot was measured with a computerized control dynamometer in a sitting position (Man, Lam, et al., 2016; Man, Leung, et al., 2016). In brief, participants were asked to sit on a height-adjustable bench so that the ankle, knee, and hip were flexed at 90 degrees at the starting position. The right foot was manually positioned and secured on a footplate using a Velcro strap. The toes were stepping out of the front-curved platform such that the MTPJ axe was aligned to the rotating axis of the dynamometer with a guided laser line projector. Twenty consecutive cycles of passive toe dorsiflexion were induced by a computer-controlled motor, which was moving from the neutral position (0^o, horizontal) to 40^o toe dorsiflexion at a constant angular velocity of 40^o/s for 20 cycles (Figure 1, Man, Leung, et al., 2016). The average peak torque of middle 10 cycles (i.e., 6th to 15th cycles) was selected to calculate the overall torque value for each participant. The joint stiffness was the overall torque value divided by maximum angular displacement and reported to high within-day (ICC = 0.91, 95% CI = 0.67-0.98) and between-day repeatability (ICC = 0.91, 95% CI = 0.67-0.98) (Man, Leung, et al., 2016).

**** Insert Figure 1 around here ****

Countermovement jump (CMJ) tasks

Single CMJ, consecutive CMJ, and running CMJ were selected in this study as these movements are commonly used to assess explosive strength of the lower body and are correlated to actual jumping performance in basketball (Castro-Pinero et al., 2010; Lam et al., 2020; Miura et al., 2010; Namdari et al., 2011). Before data acquisition, standing reach height of participants were recorded using the Vertec equipment (Vertec, Sports Imports, Hilliard, OH, USA) as a baseline for all three jump conditions. For single CMJ, participants commenced by standing upright with their right foot standing on the force plate (AMTI, Watertown, USA, sampling frequency of 1000 Hz) and left foot on the ground. Then, the participants performed the CMJ by going into a squatted position with hip and knee bent, before extending the legs to jump up vertically using maximum effort.

For consecutive CMJs, participants were instructed to perform the same single CMJ movement but requested to perform six consecutive jumps consecutively for maximum height and minimum ground contact time (Cormack et al., 2008; Lam et al., 2020). For running CMJ, participants started at 5 m from the force platform. Then, participants ran from the start line and performed two-legged vertical CMJ when their right foot landing on the force platform (Lam et al., 2017; Sell et al., 2006). A timing system (SmartSpeed, Fusion Sport Inc., Burbank, CA, USA) was used to control the approach speed at 4.5 ± 0.4m/s, prior to the force plate (Edward et al., 2012). Participants were instructed to perform all jump trials with maximum effort. A successful jump was considered when the participant performed a double-leg take-off vertically, right foot landing on the force platform, and maintaining balance after landing.

Procedures

After anthropometric measurements were taken, passive MTPJ stiffness was measured in a seated position barefooted. All jumping trials were performed under shod conditions, as this would minimise excessive joint loading from the barefoot landing. This would also encourage participants to jump with maximum effort without alternation in movement mechanics. Also, participants performing barefoot jumps may not have executed the movements as naturally as they would have on a basketball court. To prevent confounding factors due to footwear features (e.g., bending stiffness, sole thickness), the same pair of basketball shoes (All City 3, Li Ning company, Beijing, China) were provided for all participants. Participants were asked to perform a 10-min warm-up to familiarise themselves with all CMJ performances. A total of 22 reflective markers (diameter 14 mm) were placed over pelvis and the right leg of participants (Figure 1c): four pelvis markers (left and right ASIS and PSIS), medial and lateral epicondyles of the femur, medial and lateral malleolus, three calcaneus markers (posterior upper, posterior lower of calcaneus and lateral aspects of heel counter), three foot tracking markers (medial side of first metatarsal head, upper side of second metatarsal head, and lateral side of fifth metatarsal head), and two four-marker rigid clusters which were attached onto thigh and leg segments. The markers on malleolus and femoral epicondyles were used during the static trial and then removed during the jumping trials (Lam et al., 2017). Fourteen infrared cameras (Vicon T40, Metrics Ltd, Oxford, UK, sampling at 200 Hz) were placed around the force plate in circular manner. Participants were instructed to perform six trials for each of the three CMJ tasks. The order of the movements was randomised across participants. Two-min and five-min rest periods were provided between trials and between movement tasks, respectively, based on the participants' feedback from the pilot test.

Data processing

MTPJ torque signals were filtered with a low pass filter with cut-off frequency of 60 Hz (Man, Lam, et al., 2016; Man, Leung, et al., 2016). The passive MTPJ torque were calculated by subtracting the torque resistance with the background torque. This background torque referred to the torque measured when the empty pedal was swinging in the identical motion. All marker trajectories were identified and then transferred into Visual3D software (C-Motion Inc, Germantown, USA) to define body segments and joint kinetic variables. Missing data was interpolated using three data points located before and after the missing data. The marker trajectories and GRF data were smoothed using a Butterworth forth-order low-pass filter at 13.3Hz (Yu et al., 1999) and at 100 Hz (Stefanyshyn & Nigg, 2000), respectively. The GRF data were normalised by body weight (BW) while the joint moment and power were normalised by body weight and height (BW*BH). Contact phase of a jump was defined from the initial contact of one foot to take-off, when the vertical GRF first exceeded 10N (foot contact) and reduced to 10N (take-off) (Lam et al., 2017). Jumping heights were determined as the difference between the maximum vertical position of the mid-point between the PSIS markers (CoM) in the air relative to the final standing rest position (Lam et al., 2020; Johnston et al., 2015). Take-off velocity was calculated by differentiating CoM position in an upward direction at the moment of take-off (Salinero et al., 2014).

Additionally, peak angular velocities, moments, and powers of MTP, ankle and knee joints during take-off phase were reported in this study. Peak angular velocity was defined as the maximum change in joint angle during the take-off phase. An inverse dynamic model with shank, rearfoot, and forefoot segments was used to calculate joint moments and joint power production and was calculated by taking the product of the resultant joint moment and the joint angular velocity (Lam et al., 2017; Dowling et al., 2012; Stefanyshyn & Nigg, 2000). The MTPJ was modelled as a single joint rotation about an axis perpendicular to the sagittal plane (Lam et al., 2017). Positive values for joint kinematics and kinetics denoted MTP dorsiflexion, ankle dorsiflexion and knee extension, with zero degree defined at neural standing position (Figure 2). As the first jump trial in the consecutive CMJ trials might have potential difference from that of the CMJ trials 2-6, only the data of trials 2-6 from all three jump tasks were selected for subsequent statistical analysis across all participants (Lam et al., 2016; 2020).

**** Insert Figure 2 around here ****

Statistical analysis

All statistical analyses were performed using SPSS (Version 19.0, Chicago, IL, USA). Data are reported as mean and 95% confidence interval (95% CI). Pearson's correlation coefficient (r) was employed to examine relationships between MTP passive stiffness and other performance, GRF, joint kinematic and kinetic variables. Statistical significance was set at $p < 0.05$. Effect size of Pearson's r was computed and interpreted as *small* ($|r| < 0.3$), *moderate* ($0.3 \le |r| < 0.5$) or *strong* ($|r| \ge 0.5$) (Cohen, 1998).

Results

The passive MTPJ stiffness

The 20 cycles were averaged for each participant. The mean passive MTPJ stiffness of all participants was 1.63 ± 0.71 Nm/deg.

Correlations of MTPJ stiffness and performance/GRF variables

MTPJ stiffness was positively correlated with jump height ($r = 0.492$, $P < 0.05$, *moderate*) and take-off velocity ($r = 0.474$, $P < 0.05$, *moderate*) in consecutive CMJ conditions ($P < 0.05$, Table 1), but not for the other two CMJ conditions ($P > 0.05$).

**** Insert Table 1 around here ****

Correlations of MTPJ stiffness and MTPJ variables

At single CMJ (Table 1), MTPJ stiffness was inversely correlated with peak MTPJ take-off extension velocity ($r = -0.458$, $P < 0.05$, *moderate*). There were no significant correlations between MTPJ stiffness and any variables in consecutive and running CMJ conditions ($P > 0.05$, Table 1).

Correlations of MTPJ stiffness and ankle variables

At consecutive CMJ, there were significant correlations in peak moments and powers during both take-off phase ($P < 0.05$), but not found in any peak ankle and angular velocity variables ($P > 0.05$, Table 1). MTPJ stiffness was positively correlated with peak take-off plantarflexion moment ($r = 0.680$, $P < 0.01$, *strong*), and peak ankle take-off power ($r = 0.435$, $P = 0.049$, *moderate*) in CMJ condition. There were no significant correlations between MTPJ stiffness and all ankle variables in single and running CMJ conditions ($P > 0.05$, Table 1).

Correlations of MTPJ stiffness and knee variables.

There were no significant correlations between MTPJ stiffness and all knee variables in each CMJ condition ($P > 0.05$, Table 1).

Discussion

The present study examined the association of passive MTPJ stiffness relative to other biomechanical variables in different types of jump. The primary findings were that (i) MTPJ stiffness was correlated with performance variables (jump height and take-off velocity) and ankle moment/power variables in consecutive CMJ and with peak MTPJ take-off extension velocity in single CMJ task, and (ii) MTPJ stiffness and tested take-off variables of running CMJ were not correlated. These findings suggest that the MTPJ stiffness of participants has a greater influence on ankle biomechanics and jump performance in consecutive CMJ (total 4 variables) than single CMJ (only 1 variable) and running CMJ (no variable). All of these variables (jump height, take-off velocity, peak ankle plantarflexion and power) are of direct relevance to jumping performance in the literature. One plausible explanation is that stiffer toes require greater power absorption and generation at the ankle in consecutive CMJ than in a single or running CMJ to maintain the continuous and repeated mode of movement (see Table 1), which is partly in agreement with previous studies of continuous sports biomechanics (Lam et al., 2016; 2020). Based on these findings, MTPJ stiffness as well as take-off performances on consecutive CMJ would be a better indicator of basketball talent. However, further experimental investigation is required to consider this statement further.

Higher MTPJ stiffness of participants was associated with better jumping performance (greater height and faster take-off velocity) in consecutive CMJ, but not for single CMJ and running CMJ. This may indicate that the stiffer MTPJ has a higher potential to store and release energy during consecutive movements. This statement agrees with previous studies (Zelik et al., 2015; Stefanyshyn & Nigg, 2000; Park et al., 2017), which suggested that increased passive stiffness in the MTPJ region can enhance the efficiency and/or performance in consecutive movements such as walking (Zelik et al., 2015) and running (Stefanyshyn & Nigg, 1997). The increase in performance can be explained by a reduction in energy dissipation at the MTPJ (Stefanyshyn & Nigg, 1998) or by an increase in optimal length of foot muscles and stiffness for force development (animal study on eccentric exercise program) (Radin et al., 1978). However, other studies revealed that passive stiffness has no favourable effects on muscle performance during the stretch shortening cycle (Kubo et al., 2001). For practical applications, consecutive CMJs which is the greatest asset for rebounding and blocking in basketball and volleyball (Wissel, 2012), the functional benefits of toe strength/stiffness training regime can be recommended as increased toe strength seems beneficial to jumps that are consecutive in nature. Considering the early studies that suggested athletes can optimize foot energetics with minimized negative work of the MTP during take-off phase, functional training incorporated with toe flexor strength (Goldmann et al., 2013; Morita et al., 2015) or choosing footwear with appropriate stiffness (Stefanyshyn & Wannop, 2016) can be implemented to improve jumping performances. Future research should focus on identifying the exact mechanism of performance improvement related to MTPJ stiffness in association with other lower limb kinematics.

MTPJ stiffness was not correlated with knee joint biomechanics in jump take-off among test conditions. Rather, our findings revealed that MTPJ stiffness had medium/large correlation effect on ankle kinetics including peak take-off ankle moments and powers in CMJ. This suggests that the greater MTPJ stiffness would induce higher ankle stiffness (Liu et al., 2020) or allow more energy absorption and generation by the ankle joint (Krell & Stefanyshyn, 2006) or greater ankle stiffness. Peak extension moments/powers are associated with maximum muscle efforts for energy absorption (Zhang et al., 2000) and jumping performance (Dowling et al., 2012). Since the ankle joint connects the medial and lateral gastrocnemius muscles via the large Achilles tendon for powerful plantarflexion for propulsion, it is possible that the leg muscles and the Achilles tendon can store elastic energy during the tendon elongation period and then release energy for push/take-off during jumping (Ishikawa et al., 2005). Therefore, MTPJ stiffness may have compensatory effects to the ankle joint, resulting in a significant relationship between MTPJ stiffness with ankle kinetic variables (Liu et al., 2020). From an injury perspective, higher MTPJ stiffness may be a factor in plantar ulceration of the great toe (James et al., 1988) and an MTPJ that is too stiff may lead to undesired changes in foot pronation/supination, resulting in higher rearfoot inversion during landing that could expose an athlete to injury (Nigg 2010).

No relationship was found between MTPJ stiffness and ankle kinematics, which disagrees with a previous study (Stefanyshn & Nigg, 2000). One possible reason may be due to the differences in shod conditions between studies. While Stefanyshyn and colleagues compared shoes with and without inserted carbon-fiber plates and found that the carbon-fiber plate shoes may have restricted the MTPJ range of motion for better jumping performance, our study showed individual differences in MTPJ mechanical properties alone had no relationship with lower extremity kinematics when wearing the same shoe. Another plausible reason may be due to the differences in MTPJ stiffness measurements (barefoot) and jump data measurements (shod). Further investigations of principle components and minimal number of movement components using a full-body marker set would help to identify the degree of self-organisation and movement variation across different types of jumps (Kelso 1995; Lam et al., 2009).

When interpreting our results, it is important to consider some limitations in the present study. First, male subject groups were used in this study, therefore it is difficult to generalise in relation to gender or playing position. Females may be more susceptible to higher joint laxity but lower joint stiffness than males due to higher levels of oestrogen (Boguszewski et al., 2015). Different court playing positions in basketball would have distinct physical and anthropometric attributes (Aouichaoui et al., 2012; Ducan et al., 2008), which might affect the motor control strategies and performance responses during various types of jumps. Second, only MTPJ stiffness has been measured for individual participants. Other lower extremity joint stiffness could also be measured to understand the underlying mechanisms of how joint stiffness and motor control would interact in relation to different jump types. Thirdly, all jump trials were performed in shod, instead of barefoot condition. The barefoot condition would have distinct take-off mechanics and performances compared with shod conditions. However, data from realistic scenarios (shod condition) would be more useful to understand the take-off performance in regular training and competition. In future studies, extremely large datasets using thousands of jump trials will be required for robust machine learning modelling to examine the complicated relationship between joint stiffness and anthropometry information using artificial neural networks based on the data regarding detailed performance outcomes (e.g., jump height, take-off velocity, push-off GRF) and jumping kinematics/kinetics of the lower extremity.

Conclusion

Higher MTPJ stiffness of participants was demonstrated to be associated with better jumping performance by generating greater peak ankle plantarflexion moment and peak ankle power at take-off in consecutive CMJ but not in single CMJ and running CMJ. This suggests that certain compensatory and motor control strategies may exist between MTPJ and the ankle joints in consecutive jumps. For basketball or volleyball players who require extensive consecutive jumps, functional training incorporated with toe flexor strength or footwear with higher bending stiffness can be considered to further improve jumping performances in accordance with the minimized negative MTPJ work concept.

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Figure captions

Figure 1. a) Top and b) medial views of the MTPJ passive stiffness device and c) marker placement

Figure 2. a) Vertical GRF, b) sagittal MTPJ angle, c) sagittal ankle angle, and d) sagittal knee ankle curves across time