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Running Title: Single versus consecutive jumps

Effect of consecutive jumping trials on metatarsophalangeal, ankle, and knee biomechanics during take-off and landing

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Abstract

This study examined the differences in single and consecutive jumps on ground reaction forces (GRF) as well as metatarsophalangeal (MTP), ankle and knee kinematics and kinetics during jumping take-off and landing. Eighteen basketball players performed countermovement jumps in both single and consecutive movement sessions. Synchronised force platform and motion capture systems were used to measure biomechanical variables during take-off and landing. Paired *t*-tests (or Wilcoxon signed-rank tests) were performed to examine any significant differences regarding mean and coefficient of variation in each of the variables tested. A Holm-Bonferroni correction was applied to *P*-values to control the false discovery rate of 5%. The findings indicated that consecutive jumps had lower jump height, take-off velocity and landing impact. During take-off, consecutive jumps demonstrated larger peak MTP and ankle extension velocities, knee extension moments as well as larger values for ankle and knee power generation; During landing, the consecutive jumps had larger peak MTP flexion angle, joint velocities (MTP, ankle and knee), and peak knee flexion moments and power absorption. Additionally, consecutive jumps had higher within-trial reliability (i.e. smaller CV) for peak MTP flexion angle at landing ($P<0.05$), but lower reliability (i.e. higher CV) for peak knee flexion velocity and power absorption at landing. These results suggest that the consecutive jump trials led to distinct movement kinematics and higher loading responses in jump take-off and landing.

Keywords: impact attenuation, metatarsophalangeal, joint moment, cushioning

Word Count: 223 (Abstract), 2970 (Main text)

Introduction

Jumping is the key attribute for offensive and defensive plays in basketball. Competitive basketball games require up to 70 jumps per player and include jump shots, rebounds, block shots and lay-ups (Ben Abdelkrim, El Fazaa, & El Ati, 2007; McClay et al., 1994; McInnes, Carlson, Jones, & McKenna, 1995). While rapid and repetitive jumps are often required for rebound and block actions in basketball (Wissel, 2012), these jumps can lead to strenuous loads on the lower extremities during landing. This is regarded as the common risk factor for ankle ligament, anterior cruciate ligament, and fifth metatarsal stress fracture injuries (Cumps, Verhagen, & Meeusen, 2007; McKay, Goldie, Payne, & Oakes, 2001; Siegmund, Huxel, & Swanik, 2008). Information on jump landing characteristics could be useful in predicting lower extremity injuries (van der Does, Brink, Benjaminse, Visscher, & Lemmink, 2016), and jump landing biomechanics during the performance of different jump techniques would provide additional insights into designing training regimes.

Jump landing movements have been commonly utilised to investigate the lower limb kinematics and loading characteristics across interventions (jumping type: Beardt et al., 2018; Zahradnik, Jandacka, Uchytil, Farana, & Hamill., 2015; body mass: Nin, Lam, & Kong, 2016; Footwear: Lam, Liu, Wu, Liu, Sun, 2019; Lam, Kan, Chia, & Kong, in press; Zhang, Clowers, Kohstall, & Yu, 2005). A previous study investigated jump landing biomechanics using stick landing (i.e., both feet are relatively parallel at the time of ground contact) and step-back landing (i.e., with the right lower extremity stepping back immediately upon landing) techniques after a block jump task. The findings demonstrated higher landing impacts and greater knee valgus moments during step back landing

(Zahradnik et al., 2015). Findings from this study suggested that jump-landing mechanics under sport-specific conditions may better represent the movement characteristics than the non-specific jump tasks (Beardt et al., 2018). These conclusions suggest that the further study of sport-specific movement protocols can provide additional biomechanical insights that are related to both injury prevention and performance enhancement.

To date, jump landing movements are predominantly investigated during a single isolated movement, as single movement jump trials would allow consistent task control across studied interventions in a biomechanical laboratory setting (Lam et al. 2018; Nin et al., 2016). However, realistically basketball training and competition often requires players to perform consecutive and repeated jumps for rebounding purposes (Wissel, 2012). Furthermore, previous studies comparing single and consecutive movement trials revealed distinct loading responses and movement characteristics in countermovement jumps (Cormack, Newton, McGuigan, & Doyle, 2008) and badminton lunges (Lam, Ding, & Qu, 2016). The information from consecutive jump trials are thought to be more realistic and valuable in sport training and performance compared with isolated jump trials (Howell, Gaughan, Cairns, Faigenbaum, & Libonati, 2001). While the information of consecutive jumps is well established in take-off biomechanics, the influence of consecutive jumps on landing biomechanics remains unclear. Movement characteristics and loading profiles in landing from consecutive trials may be related to injury risks and require further investigation.

Additionally, studies on jump landings failed to report any information related to the metatarsophalangeal (MTP) joint. Information on forefoot biomechanics can provide additional information to help understand how ground reaction forces are exerted on the foot (e.g., Stefanyshyn & Nigg, 2000). The information provided would also help us determine how the forces are transferred through the MTP joint to the proximal joints during jumping take-off and landing. Furthermore, the findings would be useful in the determination of the differences in force and lower limb mechanics with single and consecutive movement trials. Hence, the objective of the present study was to investigate the differences in single and consecutive jump landing trials in terms of ground reaction forces, MTP, ankle and knee kinematics and kinetics during jumping take-off and landing phases. Based on the previous investigations on consecutive movements (Jumping: Cormack et al., 2008; Badminton: Lam et al., 2016), it is expected that data resulting from consecutive trials would result in higher joint loading and excursion as well as inter-trial reliability compared with the single jumping trials. The findings from this study could be insightful for coaches and sport scientists when assessing impacts and joint loading characteristics during training and competition.

Methods

Participants

Eighteen male university basketball athletes [age = 20.9 (1.0) years; height = 1.80 (0.04) m; mass = 69.2 (7.7) kg] were recruited for this study. All participants were reported as right-leg dominant and free of any lower extremity injuries in the past six months. Leg-dominance was confirmed by asking the participants to kick a ball at a target placed 4m away as described previously (van Melick, Meddeler, Hoogeboom, Nijhuis-van der Sanden & van Cingel, 2017). All participants signed an informed consent form and ethical approval was granted by the Institutional Review Board prior to the commencement of the study.

Apparatus

All athletes performed six trials of vertical countermovement jumps in both single and consecutive jump sessions. The vertical countermovement jump is commonly used to assess the explosive strength of the lower extremities and jumping performance in basketball (Castro-Pinero et al., 2010; Namdari, Scott, Milby, Baldwin, & Lee, 2011). The movement is also a crucial manoeuvre for biomechanical research related to basketball footwear (Lam et al., in press; Lam, Lee, Lee, Ma, & Kong, 2017). A force plate (AMTI, Watertown, USA, sampling frequency of 1000 Hz) and 8-camera motion analysis system (Oxford Metrics Ltd, Oxford, sampling frequency of 200 Hz) were synchronized to collect the ground reaction forces and kinematic information during both the take-off and landing phases of all jump trials.

Procedure

After anthropometrical measurements were taken, the participants wore new standard socks and test shoes (Li Ning Wade Cloud cushion, Beijing, China). A total of 22 reflective markers (diameter 14 mm) were placed over the pelvis and the right lower extremity. This included 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 and lateral aspects of calcaneus), 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 for thigh and leg segments, respectively. The markers on the medial and lateral epicondyles were used during the static trial and then removed before commencing with the movement trials.

Prior to actual data collection, the participants performed a 10-minute standard warm-up and familiarized themselves with both single and consecutive jumps. For the single jump session, the participants were instructed to stand on the force plate and then perform the countermovement jump by going into a squatted position with hips and knees bent, followed by a quick vertical jump up as high as possible in one sequence. For the consecutive jump session, the participants were told to perform the same countermovement jump as instructed in the single jump session, but requested to initiate the next jump immediately after landing (Cormack et al., 2008). The participants were required to perform six consecutive jumps in a row. The jump task involved performing a double-leg take-off vertically with the right foot landing within the boundaries of the force platform. A jump was considered successful if the participant maintained their balance after landing. Six successful trials of both single and consecutive jumps were obtained. The trial was discarded if there was obvious slippage or discontinuity of movement. The single and consecutive sessions were randomised across participants. To minimise the effect of fatigue, 1.5-minute and 10-minute resting periods were administered between trials and between movement sessions, respectively.

Data processing

We identified marker trajectories using Vicon Clinical Manager Software (Oxford Metrics Ltd, Oxford, UK). Data were then transferred into Visual3D programme (C-Motion Inc., Germantown, USA) to define segments and joint kinetic variables. In the case of missing data, a spline interpolation was performed using three frames of data before and after the missing data. The marker trajectories data were smoothed with a Butterworth fourth order filter with a cut-off frequency of 12 Hz (Yu, Gabriel, Noble, & An, 1999). Take-off phase was defined as the period from the maximum knee flexion (i.e. the lowest CoM) to the foot taking off the ground and landing phase was defined as the period from the initial contact on the ground to the maximum knee flexion (Figure 1) (Cormack et al., 2008). The contact phase of the jump was identified from initial contact of one foot to take off, as determined by the force plate. The instant of take-off and landing were determined as the moment when the vertical GRF first reduced to 10 N (take-off) and exceeded 10 N (landing), respectively (Cormack et al., 2008; Nin et al. 2016). Jumping heights were determined as the difference between the maximum height of the midpoint between the PSIS markers (CoM) in the air and the final standing rest position (Johnston et al., 2015; Zelik & Kuo, 2012). The take-off velocity was calculated by differentiating CoM positions in upward direction at the moment of take-off (Wade, Lichtwark, & Farris, in press).

****Insert Figure 1 near here****

Peak angular velocities, moments and powers of MTP, ankle and knee joints of both take-off and landing phases were determined for this study. Peak angular velocity was defined as maximum change in joint angle during respective take-off and landing phases. Joint moments and powers were calculated with an inverse dynamic model that comprised of shank, rearfoot, and forefoot segments (Dowling, Favre, & Andriacchi, 2012; Lam et al., 2017; Stefanyshyn & Nigg 2000). Joint power was defined as the scalar product of the resultant moment and angular velocity about the joint (e.g., Stefanyshyn & Nigg, 2000). A positive value for joint kinematics and kinetics denoted knee extension, ankle dorsiflexion and MTPJ dorsiflexion; with a zero degree defined at the neutral standing position. The MTPJ was modelled as a single joint rotation about an axis perpendicular to the sagittal plane (Lam et al., 2017). The GRF data were normalised to body weight (BW), joint moment and power were normalised with body weight and body height (BW*BH).

Data analysis

As apparent from Figure 1, the first and last jumps showed distinct jump take-off and landing movement patterns in comparison to trials two to five. Therefore, only the trials two to five were used to compare means and coefficients of variation (CV) between single and consecutive sessions for each participant. Paired *t*-tests (or Wilcoxon signed-rank tests if the assumptions of normal data distribution were violated) were performed to identify any significant differences between single and consecutive jumps for all jump performance, GRF, jump take-off and jump landing variables, respectively. A Holm-Bonferroni correction was applied to *P*-values to control the false discovery rate of 5%. Effect sizes (Cohen’s *d* for paired *t*-test and *r* for Wilcoxon signed-rank test) were calculated accordingly and interpreted as: (i) small if $0.2 \leq$ effect size < 0.5; (ii) medium if

$0.5 \leq$ effect size < 0.8 and (iii) large if effect size ≥ 0.8 (Cohen, 1988).

Results

Jump performance and GRF variables

The consecutive jump trials had a significantly lower jump height [$P < 0.001$, $r = 0.88$, large effect], take-off velocity [$P < 0.001$, $r = 0.88$, large effect] and peak landing GRF [$P < 0.001$, $d = 1.35$, large effect] than the single trials (Table 1).

****Insert Table 1 near here****

Jump take-off variables

The consecutive jump trials induced significant larger peak MTP extension take-off velocity [$P < 0.001$, $d = 3.62$, large effect, Table 1], peak ankle plantarflexion velocity [$P < 0.001$, $r = 0.88$, large effect, Table 2] and joint power at take-off [$P = 0.002$, $r = 0.84$, large effect, Table 2] as well as peak knee extension moment [$P < 0.001$, $d = 2.97$, large effect, Table 3] and joint power generation at take-off [$P < 0.001$, $d = 2.97$, large effect, Table 3] compared to the single jump trials.

**** Tables 2 and 3 near here****

Jump landing variables

The consecutive jump trials had significantly larger peak MTP flexion angle [$P < 0.001$, $d = 1.39$, large effect, Table 1] and velocity [$P < 0.001$, $d = 4.65$, large effect, Table 1], peak ankle plantarflexion velocity [$P < 0.001$, $d = 2.06$, large effect, Table 2] as well as peak knee flexion velocity [$P < 0.001$, $d = 2.68$, large effect, Table 3], peak flexion moment [$P < 0.001$, $d = 1.82$, large effect, Table 3] and joint power absorption at landing [$P < 0.001$, $d = 1.78$, large effect, Table 3] than the single jump trials.

Coefficient of variation variables

Analysis of CV data revealed that no significant difference between single and consecutive jump conditions for all jump performance, GRF as well as ankle kinematics and kinetics variables (Tables 1 & 2).

For the MTP joint, the consecutive jump trials had lower CV for peak flexion angle [$P = 0.002$, $r = 0.71$, medium effect] at landing than the single jump trials, but no significant differences were determined during the take-off phase (Table 1). For the knee joint, the consecutive jump trials had higher CV for peak knee flexion velocity [$P < 0.001$, $d = 1.54$, large effect] and peak joint power at landing [$P = 0.002$, $d = 1.39$, large effect], but no significant difference were determined during take-off phase (Table 3).

Discussion

This study examined the biomechanical responses of jumping take-offs and landings associated with single and consecutive movement trials to establish the scientific guidelines for basketball related research. Compared to the single jump trials, we found that consecutive jumps led to inferior jump performance and lower peak landing impact. During take-off, consecutive jumps demonstrated larger peak joint extension velocities (MTP, ankle and knee), knee extension moment and joint power. During landing, larger peak MTP flexion angle, higher peak joint velocities (MTP, ankle and knee), and peak knee flexion moment and joint power were found in consecutive jumps. While consecutive jumps demonstrated poorer performances, larger joint extension velocities and greater joint loadings suggest a greater activity volume and muscular ligament strains in rapid consecutive take-off movements, which could be considered as a potential modifiable risk factor in lower extremity injuries (Beardt et al., 2018; Sprague, Smith, Knox, Pohlig, & Gravare Silbernagel, 2018; Zahradnik et al., 2015). An alternative explanation could be the stretch-shortening cycle associated with the consecutive jumps that required participants to reverse the downward velocity into the upward velocity immediately after landing, which is in line with the biomechanics and performance findings in drop jump tasks (involve jumping vertical immediately after landing) (Johnston et al., 2015; Young, Pryor, & Wilson, 1995). Furthermore, Young et al. (2015) argued that the time-constraint instruction (drop jump for height and short contact time) would lead to a performance trade-off (i.e. lowered jump height) compared to the countermovement jump. Studying muscular activation would help to understand the underlying motor control mechanisms in performance associated with consecutive type of movements.

During landing, basketball athletes performing consecutive jumps exhibited lower ground reaction force impacts than the single jumps trials, which is consistent with previous studies investigating various types of landing (Cormack et al., 2008; Lam et al., 2016). To achieve consecutive jumps, our participants demonstrated larger peak MTP, ankle, and knee flexion and extension velocities in both the landing and take-off phases, respectively, which could explain why larger knee power was observed in both phases. The current findings also suggest that assessing repeated or consecutive movement trials could be a better alternative to evaluate jump landing biomechanics that may be related to injuries and performance, as repeated jumps require higher physical demands (Cormack et al., 2008; Hong, Wang, Lam & Cheung, 2014; Lam et al., 2016) and are considered highly relevant to realistic sports movements (Beardt et al., 2018; Besier, Lloyd, Ackland & Cochrane, 2001; Lam et al., 2016; Taylor et al., in press; Zahradnik et al., 2015).

Compared to single jump trials, consecutive jumps had a higher within-trial reliability (i.e., smaller CV) for peak MTP flexion angle at landing, but lower reliability (i.e., higher CV) for peak knee flexion velocity and peak power at landing. Increased reliability between trials may indicate more consistent execution of consecutive ballistic movements (Cormack et al., 2008). The higher CV in peak knee velocities and joint loading found in consecutive jumps would also suggest that a consecutive jumping task may demand a wider range of landing strategies from the athletes (van Emmerik, Miller & Hamill, 2014). The distinct inter-trial reliability patterns between MTP and knee joints could be explained by the different functions of MTP and knee joints in jump landing, as each jump type requires very different movements and coordination to optimise jump-landing movement (Johnston et al., 2015).

When interpreting the findings, it is important to consider some experimental limitations. Firstly, a single male university athlete group was recruited in this study and it is not generalisable to other groups. Different genders, playing levels and positions may have shown remarkable differences in jumping intensity and frequency in basketball training and competition (Ben Abdelkrim et al., 2007; Brauner, Zwinzscher, & Sterzing, 2012; Hootman, Dick,

& Agel, 2007; Quatman, Ford, Myer, & Hewett, 2006). Secondly, we did not measure hip mechanics, electromyography and movement coordination during jumping take-off and landing. Hip joint would play different roles and contributions in different jumping task conditions (Johnston et al., 2005). Future studies could examine hip mechanics, muscular activation, and movement stability to understand the underlying mechanisms and strategies associated with single and consecutive jumps.

Conclusion

Assessing repetitive jump performance may be valuable in sporting performance. Consecutive jump trials produced higher joint loading and faster joint velocity. Furthermore, the consecutive trials showed better within-trial reliability at the MTP joint but lower reliability at the knee joint. These result suggest that the consecutive jumping trials led to different movement kinematics and higher loading responses in comparison to a series of single jumps. These findings could be insightful for training regimes in basketball jumping activities.

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Figure Caption

Figure 1. Vertical GRF profiles and definitions of the take-off and landing phases in single and consecutive jump conditions