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Abstract: Purpose: When investigating lower limb landing biomechanics researchers often assume movement symmetry between a participants right and left lower limbs for the simplicity of data collection and analysis, despite the fact that landing tasks often involve dual-limb motion. However, whether lower limb symmetry can be assumed when investigating dynamic, sport-specific movements such as the stop-jump, has not been investigated. Therefore, this study aimed to determine whether there were any significant differences in selected kinetic, kinematic and muscle activation patterns characterising lower limb biomechanics displayed by the dominant limb compared to the non-dominant limb of participants during a stop-jump task. Methods: Sixteen male athletes with normal patellar tendons on diagnostic imaging performed five successful stop-jump trials. Patellar tendon forces (FPT), ground reaction forces, three-dimensional kinematics, and electromyographic activity of seven lower limb muscles were recorded for the dominant and non-dominant lower limb during each trial. Results: During the horizontal landing phase, the dominant lower limb sustained a significantly higher FPT, and peak net knee joint extension moment compared to the non-dominant lower limb. Furthermore, during the vertical landing phase, the dominant lower limb sustained significantly lower vertical but higher posterior ground reaction forces compared to the non-dominant lower limb. Other variables did not significantly vary as a function of lower limb dominance.Conclusions: It is recommended that researchers clearly identify their primary outcome variables and ensure their experimental design, particularly in terms of lower limb dominance, provides an appropriate framework to investigate possible mechanics underlying unilateral and bilateral knee joint injuries during dual-limb movements such as the stop-jump task.

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MANUSCRIPT

Lower limb movement symmetry cannot be assumed when investigating the stop-jump landing

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ABSTRACT

Purpose: When investigating lower limb landing biomechanics researchers often assume movement symmetry between a participant's right and left lower limbs for the simplicity of data collection and analysis, despite the fact that landing tasks often involve dual-limb motion. However, whether lower limb symmetry can be assumed when investigating dynamic, sport-specific movements such as the stop-jump, has not been investigated. Therefore, this study aimed to determine whether there were any significant differences in selected kinetic, kinematic and muscle activation patterns characterising lower limb biomechanics displayed by the dominant limb compared to the non-dominant limb of participants during a stop-jump task.

Methods: Sixteen male athletes with normal patellar tendons on diagnostic imaging performed five successful stop-jump trials. Patellar tendon forces (F_{PT}), ground reaction forces, three-dimensional kinematics, and electromyographic activity of seven lower limb muscles were recorded for the dominant and non-dominant lower limb during each trial.

Results: During the horizontal landing phase, the dominant lower limb sustained a significantly higher F_{PT}, and peak net knee joint extension moment compared to the non-dominant lower limb. Furthermore, during the vertical landing phase, the dominant lower limb sustained significantly lower vertical but higher posterior ground reaction forces compared to the non-dominant lower limb. Other variables did not significantly vary as a function of lower limb dominance.

Conclusions: It is recommended that researchers clearly identify their primary outcome variables and ensure their experimental design, particularly in terms of lower limb dominance, provides an appropriate framework to investigate possible mechanics underlying unilateral and bilateral knee joint injuries during dual-limb movements such as the stop-jump task.

Keywords: Patellar tendinopathy, patellar tendon, knee, biomechanics; experimental design.

INTRODUCTION

Paragraph Number 1. Researchers investigating the biomechanics of dual-limb landing tasks often assume movement symmetry (32, 34) for the simplicity of data collection and analysis (23, 32). However, whether this assumption is valid when analysing dynamic dual-limb landing tasks has not been established. Lower limb asymmetry is a critical factor to consider as it can lead to overloading of one lower limb (34) and, in turn, can contribute to the development of unilateral lower limb injuries such patellar tendinopathy (11, 13, 18). Lower limb asymmetry can also place both limbs at an increased risk of a knee joint injury (17, 21, 22), as the dominant lower limb may sustain higher forces from its increased dependence and loading, whereas the weaker lower limb's ability to tolerate typical forces may also be compromised (17). Furthermore, unilateral and bilateral patellar tendinopathy are thought to have different aetiologies (11, 18), potentially indicating that these are distinct entities necessitating separate treatment (13). Therefore, lower limb symmetry in dual-limb landing tasks is an essential experimental design consideration.

Paragraph Number 2. The biomechanics of dual-limb dynamic sporting movements, such as the stop-jump, have been extensively investigated in an attempt to identify potential risk factors associated with common knee joint injuries like patellar tendinopathy (6-8, 35, 36, 38, 39), as these movements are repetitively performed in sports that have a high prevalence of this injury (1, 14, 37). Previous researchers investigating lower limb landing biomechanics of a stop-jump task have frequently collected and/or analysed data for only one lower limb, relying on the assumption of movement symmetry when interpreting the data. The limb tested during these dual-limbed stop-jump tasks has varied from the dominant lower limb (8, 19, 38, 39), the right lower limb (7, 35, 40) or has not been reported (5, 6, 36). Although movement symmetry has been investigated in drop landings (17, 27, 34), conflicting results have been reported due to between-study differences in research design, statistical analyses (34) and definitions of lower limb dominance. The application of the results of these studies to knee injury mechanisms is also limited as drop landing tasks do not replicate whole game-like movements (15, 16), and it is questionable whether they simulate the landing phase of a whole jump-landing movement task (15). It remains unknown, therefore, whether lower limb symmetry can be assumed when investigating a dynamic, dual-limb sport-specific movement such as the stop-jump.

Paragraph Number 3. Given the paucity of research investigating lower limb symmetry during dynamic movements, this study aimed to investigate whether there were any significant differences in selected kinetic, kinematic and muscle activation patterns characterising lower limb biomechanics displayed by the dominant limb compared to the non-dominant limb of participants during a stop-jump task. It was hypothesised that, relative to the non-dominant limb, the dominant lower limb would: (i) sustain higher patellar tendon loading and utilise a different lower limb landing strategy during the horizontal landing phase (in which they had leapt horizontally forward off one lower limb before landing on both feet) but (ii) not the vertical landing phase of the stop-jump task (in which they had jumped vertically of both lower limbs before landing on two feet).

METHODS

Participants

Paragraph Number 4. Sixteen male basketball (n = 7) and soccer (n = 9) athletes (mean age = 22.4 ± 2.9 years; height = 182.1 ± 8.7 cm; mass = 75.7 ± 10.1 kg), who reported no history of lower limb injuries that required surgery, were recruited. The patellar tendon morphology of all participants was documented as normal on diagnostic imaging by an experienced musculoskeletal radiologist using a 13 MHz linear array ultrasound transducer (Siemens Antares, Siemens AG, Germany). Written informed consent was obtained from each participant prior to data collection and all methods were approved by the institution's Human Research Ethics Committee (HE06/205).

Experiment Task

Paragraph Number 5. The stop-jump task performed in this study involved two landing phases, a horizontal landing phase, immediately followed by a vertical landing phase **(Figure 1)**. The horizontal preparation phase required the participants to accelerate forwards for four steps towards two force platforms (mean (SD) approach speed 4.5 (0.4) $m.s^{-1}$ measured using infrared timing lights; OnSpot, University of Wollongong). When near the force platforms, the participants then leapt horizontally forwards to land on both feet, with each foot simultaneously contacting a separate force platform (horizontal landing phase). Participants then immediately jumped vertically upwards off the ground to strike a ball, suspended from the ceiling, with both hands (mean (SD) vertical jump height 57 (5) cm; vertical preparation phase). Lastly, they landed on both feet a second time, with each foot again simultaneously contacting a separate force platform (vertical landing phase). The effort at which participant's performed the task was standardized by using a set starting position away from the force platform to ensure a four step approach, and by positioning the ball at the maximum height each participant could touch the ball with both hands to ensure a consistent jump height.

<insert Figure 1 about here>

Experimental Procedure

Paragraph Number 6. Each participant's height, body mass, lower limb dimensions and ankle joint range of motion (3) were evaluated. Lower limb leg dominance was based on their preferred kicking leg (17) and all participants were right leg dominant. After completing a 5-10 minute warm-up of cycling on an ergometer (Monark Model 818E, Sweden), each participant was then familiarised with the stop-jump task before performing approximately five successful stop-jump trials, where a successful trial was defined as a participant placing each foot wholly on a separate force platform during both landing phases and contacting the suspended ball with both hands. During each trial the ground reaction forces generated at landing were recorded (1000 Hz) using two calibrated multichannel force platforms (Type 9281B; Type 9253B; Kistler, Winterthur, Switzerland) embedded in the floor, with each platform connected to a multichannel charge amplifier (Type 9865A; Type, 9865B; Kistler, Winterthur, Switzerland). The participant's three-dimensional lower limb motion was recorded (100 Hz) using a calibrated Opto*TRAK*® 3020 motion analysis system (Northern Digital, Waterloo, Canada). Infrared light-emitting diodes were placed bilaterally on each participant's lower limbs and pelvis, on the shoe at the first and fifth metatarsal head and mid anterior foot, lateral and medial malleolus, lateral leg, anterior distal and anterior proximal leg, lateral and medial femoral epicondyle, lateral femur, anterior distal femur, anterior proximal femur, greater trochanter, anterior superior iliac spine and iliac crest. To avoid losing view of the infrared light-emitting diodes, the participants wore minimal clothing (a t-shirt and shorts), and their own socks and athletic running shoes.

Paragraph Number 7. Electromyographic activity was recorded bilaterally for vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), tibialis anterior (TA), and medial gastrocnemius (MG) using two Telemyo systems (Noraxon, Scottsdale, AZ). Following standard preparation (2), bipolar silver-silver-chloride surface electrodes (Ambu® Blue Sensor M, electrode size = 40.8 x 32 mm, detection area = 13.2 mm) were placed longitudinally on each muscle belly (inter-electrode distance of 20 mm). A common reference electrode was located on the tibial tuberosity of each lower limb. The electromyographic signals for each lower limb were sampled (1000 Hz, bandwidth 16-500 Hz) and relayed from the two TeleMyo 900 battery powered transmitters (Noraxon, Arizona, USA), firmly fixed around the participant's waist, to two TeleMyo 900 receivers. The kinetic, kinematic and electromyographic data were time synchronised and collected using First Principles software (Version 1.00.2, Northern Digital, Waterloo, Canada).

Data Reduction

Paragraph Number 8. Analysis of the kinematic and kinetic data was performed using Visual 3D software (Version 3, C-Motion, Germantown, MD). The raw ground reaction force data were initially filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter (f_c = 50 Hz) before calculating the ground reaction force variables. The raw kinematic coordinates, ground reaction forces, free moments and center of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter (f_c = 18 Hz) before calculating individual joint kinematics, internal knee joint moments and patellar tendon forces (4). The patellar tendon forces were calculated by dividing the net knee joint moment by the patellar tendon moment arm (30). Patellar tendon moment arms were calculated as a function of knee joint angle using the method of Herzog and Read (20).

Paragraph Number 9. The raw electromyographic signals were filtered using a fourth-order zero-phase shift Butterworth (high-pass f_c = 15 Hz) to eliminate any movement artefact. To quantify temporal characteristics of the muscle bursts, the filtered electromyographic data were full-wave rectified, filtered with a 20 Hz low pass filter and then full-wave rectified again to create linear envelopes that were then screened using a threshold detector (8% of the maximum amplitude) (12) via custom software (LabVIEW 8, National Instruments, Austin, TX). Each individual muscle's filtered signal was visually inspected to confirm the validity of the calculated results of the temporal characteristics of the muscle bursts to minimise the probability of error.

Data Analysis

Paragraph Number 10. The jump height attained by each participant during the stop-jump movement was defined as the difference in the maximum vertical displacement of the greater trochanter marker minus the vertical displacement of the same marker measured while each participant stood erect and motionless. The two landing phases within the stop-jump movement were then identified from the vertical ground reaction force-time curve as (i) the "horizontal" landing phase and (ii) the "vertical" landing phase **(16)**. The primary outcome variable analysed during these two landing phases was the peak patellar tendon force (F_{PT}). Secondary variables analysed during the same two landing phases included the peak vertical ground reaction force (F_V); peak anterior-posterior ground reaction force (F_{AP}); ankle, knee and hip joint kinematics; and the time of the onset and peak activity of each of the seven lower limb muscles relative to the time of the F_{PT} in each landing phase. Loading rate of the F_V (LR F_V, $BW.s^{-1}$) was calculated by dividing the F_V by the time interval between initial foot-ground contact (IC) to the time of the F_V. Loading rate of the F_{PT} (LR F_{PT}, $BW.s^{-1}$) was calculated by dividing the F_{PT} by the time interval between IC to the time of the F_{PT}. The temporal events (IC, time of the F_V and F_{AP}) were defined using the 18 Hz filtered kinetic data, with IC defined when the ground reaction force exceeded 30 N.

Statistical Analysis

Paragraph Number 11 Means and standard deviations were calculated for each kinetic, kinematic and muscle activity outcome variable for the participants' dominant and non-dominant lower limbs during the horizontal and vertical landing phases of the stop-jump task. After confirming normality and equal variance, the data were analysed using a series of paired *t*-tests to determine whether there were any significant differences ($P < 0.05$) in the variables when comparing the dominant and non-dominant lower limb data. It was assumed that limb symmetry was evident when no statistically significant between-limb difference was identified. To show the magnitude of the effects, effect sizes were calculated and magnitudes were assessed using the following criteria: to 0.19 = trivial; 0.20-0.49 = small; 0.50-0.79 = moderate; and >0.80 = large (9). Although multiple statistical tests were conducted, increasing the chance of incurring an error, no adjustment to the alpha level was deemed necessary given the exploratory nature of the study and the low cost associated with incurring an error. All statistical procedures were conducted using SPSS Statistical Software (Version 15, SPSS Inc., Chicago, IL).

RESULTS

Patellar Tendon Loading and Ground Reaction Forces

Paragraph Number 12. During the horizontal landing phase, the participants' dominant lower limb generated a significantly higher F_{PT}, with a significantly faster F_{PT} loading rate and higher peak net knee joint extension moment relative to their non-dominant lower limb, although the F_V and F_{AP} were symmetrical (Table 1). In contrast, during the vertical landing phase, the F_{PT} and F_{AP} were symmetrical, despite the participants' dominant lower limb generating a significantly lower F_V relative to the non-dominant lower limb (Table 1). During both landing phases, participants displayed symmetry in the timing of their foot placement whereby both lower limbs contacted the ground at a similar time (negative value indicates the right lower limb contacted the ground first; horizontal landing phase = -10 ± 18 ms; vertical landing phase = -11 ± 21 ms).

<insert Table 1 about here>

Joint Kinematics

Paragraph Number 13. Most of the lower limb kinematic variables analysed during the horizontal and vertical landing phases of the stop-jump task did not differ significantly between the participants' dominant and non-dominant lower limbs (Table 2 and Table 3). Knee joint asymmetries were evident during both the horizontal and vertical landing phases, whereby relative to the non-dominant lower limb, the participants' dominant lower limb displayed significantly less knee flexion at IC, and greater knee external rotation during the entire landing phase from IC to the times of the F_V and the F_{PT} (Table 2 and 3). During the horizontal landing phase only, participants displayed significantly increased forefoot abduction velocity at the time of the F_V, and increased ankle dorsiflexion velocity and tibial segment velocity (dominant = -335 ± 82 °.s^{-1}; non-dominant = -283 ± 64 °.s^{-1}; $P = 0.042$) at the time of the F_{PT} when landing on their dominant compared to the non-dominant lower limb. During the vertical landing phase of the task, the participants' dominant lower limb displayed a significantly greater forefoot abduction angle at the time of the F_V, decreased ankle dorsiflexion velocity at IC, and increased ankle inversion velocity at the time of the F_V when compared to the non-dominant lower limb.

<insert Table 2 and Table 3 about here>

Paragraph Number 14. Hip kinematics did not significantly differ between limbs throughout the entire horizontal landing phase. However, during the vertical landing phase, the participants displayed significantly less hip flexion at IC and at the time of the F_V, a slower hip flexion velocity at IC, and greater hip external rotation during the entire landing phase from IC to the times of the F_V and the F_{PT} when landing on their dominant compared to their non-dominant lower limb (Table 2 and 3). Throughout both landing phases and for both lower limbs, large variability was evident, particularly in the hip kinematic data, as reflected in the large standard deviations.

Muscle Activation Patterns

Paragraph Number 15. No significant between-limb differences were found in the muscle onsets or peak muscle burst activity relative to the time of the F_{PT} during either landing phase (Table 4 and 5).

<insert Table 4 and Table 5 about here>

DISCUSSION

Paragraph Number 16. Lower limb symmetry was observed in most of the kinetic, kinematic and muscle activation data during both the horizontal and vertical landing phases of the stop-jump task, and supports this study's hypothesis (ii) but not hypothesis (i). These finding are consistent with previous research that has investigated a vertical landing task and reported movement symmetry (27), although they are in contrast to others who have reported movement asymmetry (17, 34). Where statistical significant differences in lower limb kinematics were found in the present study, the magnitude of the absolute differences was often functionally irrelevant, as indicated by a trivial or small effect size. For example, the mean difference in knee flexion at IC during the vertical landing phase was 1.7°, with a trivial effect size of 0.29, and these mean differences were accompanied by large variability in the data (for example, hip kinematics). These results imply that most of the lower limb kinematics displayed by participants during both landing phases of a stop jump task in the present study were relatively symmetrical. There were, however, several significant between-limb differences in the kinetic variables, which in combination with some of the kinematic variables, are important to consider in experimental design.

Paragraph Number 17. During the horizontal landing phase, the participants generated a significantly higher F_{PT} for their dominant lower limb relative to their non-dominant lower limb. This between-limb difference in F_{PT} was due to the dominant lower limb displaying a significantly higher peak net knee joint extension moment, combined with a smaller patellar tendon moment arm due to significantly less knee flexion (20). We speculate that the higher net knee joint extension moment was due to a combination of factors, including strong trends for a higher F_V and F_{AP}, a faster knee joint velocity at the times of the F_V and F_{PT}, and the significantly faster tibial segment velocity at the time of the F_{PT} noted for the dominant lower limb relative to its non-dominant counterpart. Although we acknowledge that the strong trends are not statistically significant (range p = 0.06 - 13), there is a substantial likelihood that the effect of F_V, F_{AP}, and knee joint velocity at the times of the F_V and F_{PT} are clinically meaningful due to the effect sizes (d = 0.43; d = 0.53; d = 54; d = 0.62, respectively).

Paragraph Number 18. This asymmetrical patellar tendon loading noted during the horizontal landing phase suggests that in studies where the magnitude of the patellar force is a primary outcome variable, the participants' dominant lower limbs should be tested. Furthermore, as excessive patellar tendon loading is a risk factor for patellar tendinopathy (10, 31, 33), future research investigating the biomechanics of knee joint injuries in horizontal landings should not assume lower limb symmetry and should investigate whether lower limb asymmetry increases the risk of an athlete sustaining a knee joint injury.

Paragraph Number 19. Interestingly, the asymmetry noted in the F_{PT} during the horizontal landing phase was not evident during the vertical landing phase of the stop-jump task, supporting our initial hypothesis **(ii)**. Furthermore, although the dominant lower limb generated significantly lower F_V compared to the non-dominant lower limb, the effect size was trivial and indicates symmetry in the F_V generated between lower limbs. These results suggest that when investigating vertical landings kinetics either lower limb could be tested, although the relevance of using vertical jumping tasks, such as drop jumps, to investigate mechanics of knee injuries such as patellar tendinopathy is questionable (15).

Paragraph Number 20. It is noted that there were some significant between-limb differences in the lower limb kinematics, particularly knee rotation during both landing phases and hip flexion during the vertical landing phase. Therefore, researchers investigating joint kinematics during dynamic landing tasks are encouraged to account for such between-limb differences in their experimental design.

Paragraph Number 21. The preparatory muscle activation strategies used by the participants during the horizontal and vertical landing phases of the stop-jump task were consistent with previous research (5). Although no between-limb differences in muscle onsets or peak muscle burst activity relative to the time of the F_{PT} were found, high variability was evident in all the muscle activation data, which was consistent with previous landing studies (15, 28). This reflects the individual muscle recruitment strategies used by participants during dynamic landing tasks.

Paragraph Number 22. Several definitions have previously been used to classify the dominant lower limb, including a participant's preferred kicking leg (17, 26), the leg with which they can kick a ball the farthest (27), the lower limb used for support (26), or the limb used to predominately jump with (13). The current study defined the dominant lower limb as the preferred kicking leg, which coincidently was the right lower limb for all the participants, and the limb that sustained significantly higher F_{PT} during the horizontal landing phase compared to the non-kicking leg. Interestingly, athletes with unilateral and bilateral patellar tendinopathy have also been found to predominately jump with their leg right lower limb (13). It is important to note, however, that if the dominant lower limb in the current study had been selected as the support lower limb (the lower limb used to takeoff prior to the horizontal landing phase (8, 38, 39)), the participants' dominant lower limb would have predominately (62%) been their left lower limb. That is, the non-dominant non-support leg (the opposite lower limb to that used to takeoff prior to the horizontal landing phase), sustained significantly higher F_{PT} during the horizontal landing phase compared to the support lower limb. Regardless of whether the right lower limb in the current study was defined as dominant or non-dominant, it sustained significantly higher F_{PT} during the horizontal landing phase compared to the left lower limb. This suggests that when investigating lower limb movement symmetry of the landing phases of a stop-jump task, the definition used to classify the dominant lower limb may not be critical, as long as each participant's limb is classified using the same definition, preferably using a method that is relevant to the task under investigation.

Paragraph Number 23. We acknowledge limitations in the current experimental design. The two-dimensional model used to estimate patellar tendon force will underestimate the patellar tendon force as it uses the net knee joint moment to estimate patellar tendon force. This calculation does not account for the flexor moment produced by the hamstring or gastrocnemius muscles, which must be compensated for by a higher knee extensor moment (24), or the different anthropometry of each participant's patellar tendon moment arm, which was not scaled. It has been suggested that the patellar tendon should be modeled three-dimensionally due to its orientation in the sagittal and coronal planes. However, only two-dimensional linear regression equations exist for the patellar tendon (20, 29), and these methods do not scale the moment arm according to the participant's anthropometry. Furthermore, if the patellar tendon is modeled as a solid structure to estimate stresses and strains, regional strain pattern variations within the patellar tendon will be evident (25). These limitations should be addressed by developing a three-dimensional patellar tendon model with regional variations in stress that can be implemented in future studies to confirm our findings.

CONCLUSIONS

Paragraph Number 24. Significant lower limb movement asymmetry was displayed for some important kinetic and kinematic variables that have been associated with knee joint injuries during landing tasks, and it is recommended that researchers clearly identify their primary outcome variables and ensure that their experimental design accounts for any possible effects of limb dominance. This will ensure their experimental design, particularly in terms of lower limb dominance, provides an appropriate framework to investigate possible mechanics underlying unilateral and bilateral knee joint injuries during dynamic landing tasks such as the stop-jump task.

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CAPTIONS

TABLE 1. Effect of lower limb dominance on the mean (± SD) forces (normalized to body weight) generated during the horizontal and vertical landing phases of a stop-jump task.

TABLE 2. Effect of lower limb dominance on the mean (± SD) joint angles (°) and velocities (°.s^{-1}) displayed during the horizontal landing phase of a stop-jump task.

TABLE 3. Effect of lower limb dominance on the mean (± SD) joint angles (°) and velocities (°.s^{-1}) displayed during the vertical landing phase of a stop-jump task.

TABLE 4. Effect of limb dominance on the mean (± SD) times of the onset of muscle activation and the peak muscle activity relative to the time of the peak patellar tendon force (F_{PT}) generated during the horizontal landing phase of a stop-jump movement.

TABLE 5. Effect of limb dominance on the mean (± SD) times of the onset of muscle activation and the peak muscle activity relative to the time of the peak patellar tendon force (F_{PT}) generated during the vertical landing phase of a stop-jump movement.

FIGURE 1. Phases of the stop-jump task.

TABLE 1

	Horizontal Landing Phase				Vertical Landing Phase			
	Dominant	Non-dominant	d^a	*p*	Dominant	Non-dominant	d^a	*p*
F_V (BW)	2.1 ± 0.5	1.9 ± 0.9	0.43	0.13	2.6 ± 0.5	2.8 ± 0.5	0.54	0.05*
F_{AP} (BW)	1.1 ± 0.3	0.9 ± 0.4	0.53	0.09	0.5 ± 0.1	0.5 ± 0.1	0.04	0.83
F_{PT} (BW)	6.8 ± 1.6	5.8 ± 1.6	0.58	0.02*	5.3 ± 1.1	5.1 ± 1.1	0.17	0.55
Knee moment (Nm.kg^{-1})	3.2 ± 0.8	2.7 ± 0.7	0.60	0.02*	2.4 ± 0.4	2.6 ± 0.5	0.29	0.22
LR F_V (BW.s^{-1})	83 ± 39	71 ± 35	0.32	0.16	60 ± 29	62 ± 31	0.39	0.71
LR F_{PT} (BW.s^{-1})	93 ± 22	81 ± 24	0.52	0.05*	57 ± 16	59 ± 18	0.08	0.64
IC-F_V (ms)	34 ± 12	37 ± 20	0.26	0.37	60 ± 16	60 ± 18	0.02	0.87
IC-F_{AP} (ms)	40 ± 13	42 ± 15	0.16	0.57	14 ± 3	14 ± 4	0.04	0.95
IC-F_{PT} (ms)	75 ± 15	76 ± 15	0.00	0.85	92 ± 17	93 ± 12	0.05	0.80

Peak vertical ground reaction force (F_V), peak anterior-posterior ground reaction force (F_{AP}), peak patellar tendon forces (F_{PT}), loading rate of the F_V (LR F_V), loading rate of the F_{PT} (LR F_{PT}), time interval between initial foot-ground contact (IC) to the time of the F_V (IC-F_V), time interval between IC to the time of the F_{AP} (IC-F_{AP}), and time interval between IC to the time of the F_{PT} (IC-F_{PT}).

[a]effect size.

*Indicates significant difference in limb dominance $P < 0.05$.

TABLE 2

Variables	At the time of IC				At the time of the peak F_V				At the time of the peak F_{PT}			
	Dominant	Non-dominant	d^a	p	Dominant	Non-dominant	d^a	p	Dominant	Non-dominant	d^a	p
Joint angles (°)												
Ankle dorsiflexion	63.4±21.1	65.4±14.3	0.10	0.58	59.3±8.6	61.1±8.0	0.21	0.43	60.3±17.0	66.9±7.2	0.39	0.20
Ankle eversion	49.8±22.1	52.2±20.2	0.31	0.23	46.4±11.6	47.0±12.2	0.26	0.46	48.7±9.8	48.7±9.6	0.07	0.83
Forefoot adduction	-15.6±6.0	-14.0±10.3	0.26	0.55	-11.7±8.1	-11.4±10.0	0.04	0.90	-17.0±18.6	-9.6±9.7	0.39	0.26
Knee flexion	31.1±6.1	37.1±7.0	1.00	0.04*	47.1±6.1	49.9±7.0	0.45	0.16	62.5±5.8	66.1±7.4	0.62	0.06
Knee adduction	3.3±3.9	3.1±6.3	0.06	0.90	2.3±7.5	1.2±8.6	0.16	0.62	0.0±7.8	-0.6±8.0	0.08	0.80
Knee internal rotation	-8.4±6.1	-3.9±8.5	0.74	0.05*	-6.5±8.2	-0.1±9.4	0.78	0.01*	-3.0±7.1	1.0±5.6	0.55	0.03*
Hip flexion	49.8±22.1	52.2±20.2	0.37	0.11	46.4±11.6	47.0±12.2	0.03	0.83	48.7±9.8	48.7±9.6	0.01	0.98
Hip adduction	-10.4±10.2	-4.2±11.2	0.15	0.78	-9.2±7.4	-5.9±7.3	0.47	0.32	-5.1±4.8	-3.5±7.2	0.33	0.53
Hip internal rotation	1.0±10.6	6.6±7.9	0.45	0.19	0.3±10.9	4.1±9.3	0.22	0.42	3.6±9.3	5.6±7.3	0.22	0.45
Joint velocities (°.s^{-1})												
Ankle dorsiflexion	-88±85	-75±65	0.15	0.57	-27±399	-40±364	0.03	0.86	270±76	210±91	0.78	0.04*
Ankle eversion	-1±73	-43±100	0.58	0.22	-149±248	-131±270	0.08	0.71	-81±90	-40±72	0.45	0.10
Forefoot adduction	32±46	10±74	0.47	0.37	-136±136	-50±116	0.63	0.04*	29±115	6±142	0.20	0.48
Knee flexion	153±104	101±241	0.50	0.48	561±148	482±135	0.54	0.10	500±165	398±112	0.62	0.06
Knee adduction	-60±128	-29±102	0.24	0.29	-39±132	-53±138	0.11	0.75	-35±96	-48±73	0.13	0.68
Knee internal rotation	36±82	69±161	0.40	0.39	77±88	78±241	0.02	0.98	-56±90	-24±120	0.36	0.36
Hip flexion	109±142	70±187	0.28	0.42	111±150	63±159	0.33	0.22	43±141	2±140	0.29	0.20
Hip adduction	-47±111	57±78	0.93	0.15	18±85	19±73	0.02	0.96	37±65	26±83	0.18	0.67
Hip internal rotation	29±90	30±143	0.02	0.99	111±186	38±89	0.39	0.13	54±81	26±79	0.36	0.41

Initial foot-ground contact (IC), peak vertical ground reaction force (F_V), and peak patellar tendon forces (F_{PT}).

For the above rotations: ankle dorsiflexion, ankle eversion, forefoot adduction, knee flexion, knee adduction, knee internal rotation, hip flexion, hip adduction, and hip internal rotation are positive.

[a]effect size.

*Indicates significant difference in limb dominance $P < 0.05$.

TABLE 3

Variables	At the time of IC				At the time of the peak F_V				At the time of the peak F_{PT}			
	Dominant	Non-dominant	d^a	p	Dominant	Non-dominant	d^a	p	Dominant	Non-dominant	d^a	p
Joint angles (°)												
Ankle dorsiflexion	37.1±8.0	37.0±8.6	0.01	0.98	83.2±8.4	84.1±3.9	0.11	0.62	79.9±21.9	86.6±4.0	0.31	0.24
Ankle eversion	15.8±5.0	18.6±5.8	0.54	0.13	24.1±7.5	27.1±7.8	0.11	0.63	29.3±9.9	31.0±8.4	0.15	0.52
Forefoot adduction	-11.0±6.3	-9.3±6.9	0.26	0.43	-13.4±6.7	-9.4±5.3	0.59	0.03*	-18.1±18.8	-10.1±5.5	0.42	0.17
Knee flexion	19.3±6.2	21.1±6.4	0.29	0.05*	47.3±9.4	48.9±9.5	0.17	0.13	58.6±10.9	59.6±8.3	0.09	0.53
Knee adduction	2.2±2.6	2.0±2.4	0.08	0.81	1.7±4.3	2.0±4.2	0.06	0.85	1.1±4.9	1.8±5.3	0.16	0.69
Knee internal rotation	-12.4±6.8	-6.2±7.5	0.92	0.00*	-5.1±7.6	-0.8±4.9	0.56	0.01*	-3.4±7.4	-0.1±4.9	0.43	0.05*
Hip flexion	15.8±5.0	18.6±5.8	0.54	0.01*	24.1±7.5	27.1±7.8	0.35	0.00*	29.3±9.9	31.0±8.4	0.17	0.13
Hip adduction	-7.4±2.8	-9.2±2.7	0.91	0.29*	-8.0±4.2	-8.6±3.6	0.48	0.42	-7.6±4.1	-5.3±7.0	0.56	0.34
Hip internal rotation	-3.5±7.0	0.1±5.6	0.56	0.04*	-3.4±7.0	0.6±5.0	0.60	0.03*	-0.5±5.7	3.2±4.0	0.64	0.02*
Joint velocities (°.s^{-1})												
Ankle dorsiflexion	-25±73	-63±84	0.53	0.05*	341±150	299±96	0.28	0.14	163±239	104±109	0.25	0.33
Ankle eversion	-21±58	-17±42	0.06	0.84	-138±88	-86±93	0.58	0.05*	62±411	-13±74	0.18	0.49
Forefoot adduction	17±59	24±44	0.12	0.56	-49±72	-55±76	0.09	0.76	-109±393	-31±90	0.20	0.41
Knee flexion	157±66	181±94	0.36	0.09	472±140	448±153	0.17	0.24	420±128	422±90	0.02	0.95
Knee adduction	21±31	8±26	0.43	0.26	-18±56	-2±79	0.29	0.54	61±131	17±103	0.34	0.33
Knee internal rotation	32±62	31±67	0.02	0.96	72±138	29±102	0.31	0.21	50±289	-10±138	0.21	0.41
Hip flexion	50±55	67±55	0.32	0.02*	231±110	223±121	0.07	0.58	210±132	243±140	0.26	0.30
Hip adduction	-8±28	-3±26	0.17	0.69	34±44	9±85	0.57	0.31	-9±82	-16±50	0.08	0.80
Hip internal rotation	23±39	6±58	0.45	0.34	-8±96	21±90	0.31	0.25	61±93	53±81	0.09	0.82

Initial foot-ground contact (IC), peak vertical ground reaction force (F_V), and peak patellar tendon forces (F_{PT}).
For the above rotations: ankle dorsiflexion, ankle eversion, forefoot adduction, knee flexion, knee adduction, knee internal rotation, hip flexion, hip adduction, and hip internal rotation are positive.
[a]effect size.
*Indicates significant difference in limb dominance $P < 0.05$.

TABLE 4.

Muscle (ms)	Onset of muscle activation relative to the time of F_{PT}				Peak muscle activity relative to the time of F_{PT}			
	Dominant	**Non-dominant**	d^a	p	**Dominant**	**Non-dominant**	d^a	p
Tibialis anterior	-126 ± 51	-148 ± 42	0.45	0.26	-101 ± 34	-106 ± 39	0.36	0.26
Medial gastrocnemius	-123 ± 60	-119 ± 38	0.05	0.82	-148 ± 33	-166 ± 35	0.17	0.66
Biceps femoris	-104 ± 32	-112 ± 48	0.25	0.64	-109 ± 30	-110 ± 43	0.31	0.50
Semitendinosus	-118 ± 38	-139 ± 42	0.55	0.25	-124 ± 61	-142 ± 45	0.43	0.38
Vastus medialis	-97 ± 29	-102 ± 27	0.17	0.61	-103 ± 21	-105 ± 48	0.39	0.25
Rectus femoris	-92 ± 28	-92 ± 20	0.00	0.99	-98 ± 36	-94 ± 47	0.18	0.38
Vastus lateralis	-89 ± 17	-98 ± 33	0.51	0.38	-97 ± 21	-92 ± 54	0.34	0.72

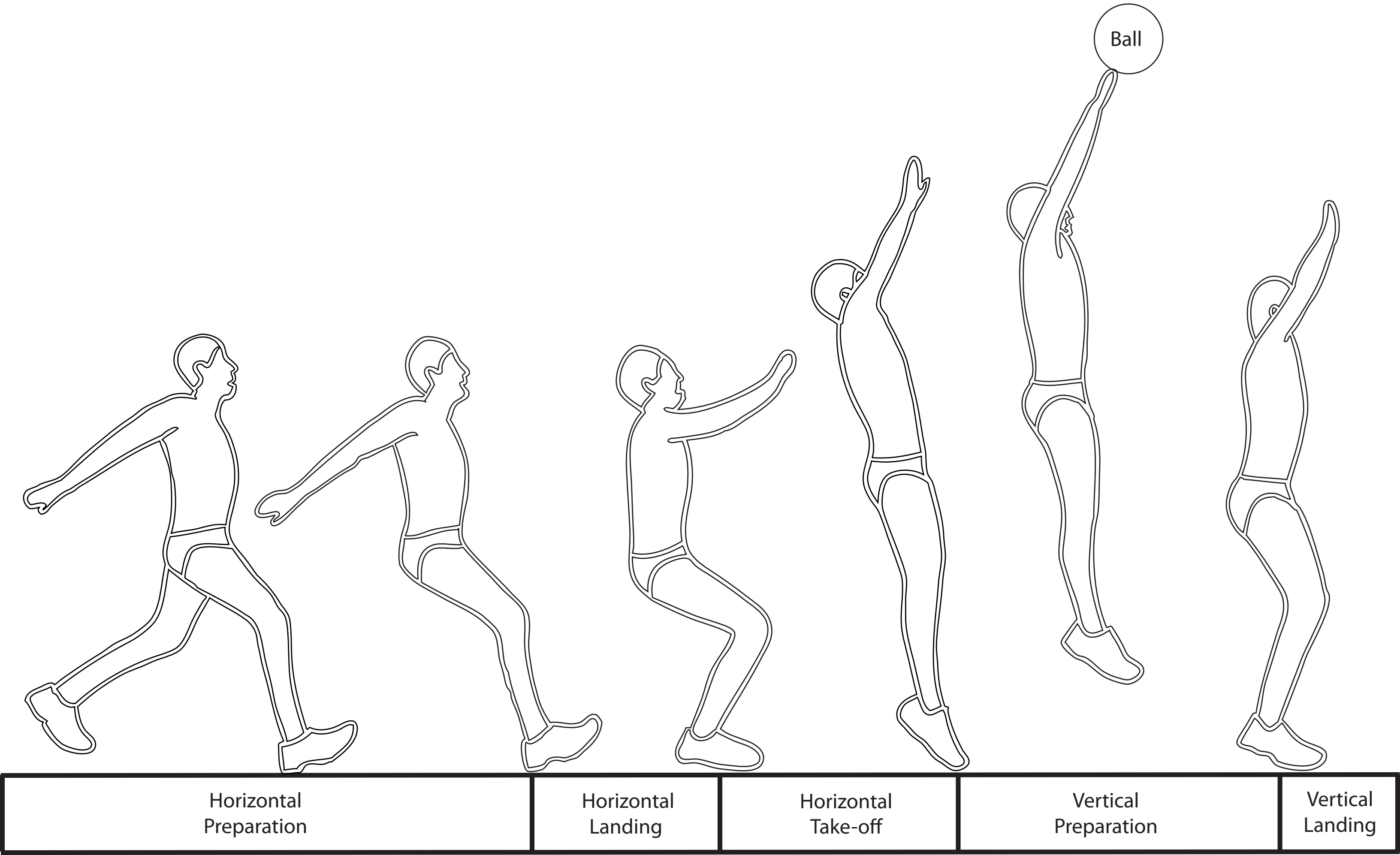
Peak patellar tendon forces (F_{PT}).
Negative values indicate muscle activation variable occurred before F_{PT}.
[a]effect size.
*Indicates significant difference in limb dominance $P < 0.05$.

TABLE 5.

Muscle (ms)	Onset of muscle activation relative to the time of F_{PT}				Peak muscle activity relative to the time of F_{PT}			
	Dominant	**Non-dominant**	d^a	p	**Dominant**	**Non-dominant**	d^a	p
Tibialis anterior	-28 ± 39	-42 ± 31	0.15	0.72	-14 ± 36	-16 ± 43	0.05	0.89
Medial gastrocnemius	-43 ± 55	-34 ± 41	0.55	0.09	-78 ± 28	-80 ± 16	0.09	0.77
Biceps femoris	-24 ± 37	-35 ± 50	0.03	0.93	-43 ± 35	-61 ± 46	0.52	0.33
Semitendinosus	-43 ± 31	-56 ± 40	0.30	0.34	-41 ± 71	-78 ± 61	0.52	0.15
Vastus medialis	-1 ± 33	-14 ± 40	0.09	0.87	-11 ± 36	-18 ± 48	0.18	0.56
Rectus femoris	4 ± 31	-2 ± 33	0.10	0.83	-21 ± 36	-24 ± 38	0.11	0.84
Vastus lateralis	9 ± 30	4 ± 36	0.05	0.90	-4 ± 32	-21 ± 47	0.56	0.15

Peak patellar tendon forces (F_{PT}).
Negative values indicate muscle activation variable occurred before F_{PT}.
[a]effect size.
*Indicates significant difference in limb dominance $P < 0.05$.

Figure


Ball
Horizontal Preparation
Horizontal Landing
Horizontal Take-off
Vertical Preparation
Vertical Landing