Journal of Biomechanics 156 (2023) 111667

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Differences in lower extremity joint stiffness during drop jump between healthy males and females

Youngmin Chun [a,*], Craig P. McGowan [b], Jeffrey G. Seegmiller [c,d], Russell T. Baker [c,d], Joshua P. Bailey [c]

[a] *Department of Kinesiology, Sonoma State University, Rohnert Park, CA, USA*
[b] *Department of Integrative Anatomical Sciences, University of Southern California, Los Angeles, CA, USA*
[c] *Department of Movement Sciences, University of Idaho, Moscow, ID, USA*
[d] *Idaho WWAMI Medical Education Program, University of Idaho, Moscow, ID, USA*

ARTICLE INFO

Keywords:
Landing mechanics
Angle-moment relationship
Jump performance
Polynomial regression model

ABSTRACT

The primary purpose of this study was to examine sex differences in lower extremity joint stiffness during vertical drop jump performance. A secondary purpose was to examine the potential influence of sex on the relationship between joint stiffness and jump performance. Thirty healthy and active individuals performed 15-drop jumps from 30 and 60 cm boxes. Hip, knee, and ankle joint stiffnesses were calculated for subphases of landing using a 2nd order polynomial regression model. Males had greater hip stiffness during the loading phase in drop jumps from both box heights than females' drop jump from 60 cm box. Also, males had a greater ground reaction force at the end of eccentric phase, net jump impulse, and jump height regardless of box height. The 60 cm box height increased knee stiffness during the loading phase, but reduced hip stiffness during the loading phase and knee and ankle stiffness during the absorption phase regardless of sex. Joint stiffnesses significantly predicted drop jump height for females ($p < .001$, $r^2 = 0.579$), but not for males ($p = .609$, $r^2 = -0.053$). These results suggest that females may have different strategies to maximize drop jump height as compared to males.

1. Introduction

Sport participation often necessitates repetitive propulsive jumps and landings, requiring lower extremity structures to interact each other and regulate the body's response to external forces. The system's interaction has been simply depicted by the spring-mass model (Blickhan, 1989). The model illustrates the interaction with an external load through the relationship between changes in leg length (Morin et al., 2005) or vertical displacement of the center of mass (COM; Arampatzis et al., 2001; Morin et al., 2005; Padua et al., 2005) and vertical ground reaction force (vGRF). The simplistic model, however, ignores how individual joints may contribute to the attenuation and absorption of an external load. In contrast, a torsion-spring model provides more insight into the behavior of individual joints' angle-moment relationship (Farley and Morgenroth, 1999; Ford et al., 2010; Horita et al., 2002; Schmitz and Shultz, 2010; Stefanyshyn and Nigg, 1998).

Joint stiffness is often used to evaluate potential indicators of performance in sport-related movements (Arampatzis et al., 2001; Farley and Morgenroth, 1999; Stefanyshyn and Nigg, 1998). For example, increased joint stiffness is likely to elicit a more efficient stretch–-shortening cycle (SSC), by increasing the amount of stored energy (Hamill et al., 2015). Modulation to increase joint stiffness can occur through increased torque or by a reduction in joint angle in response to the load. These modulations may induce greater stress, and thus strain, on the muscle–tendon units. Therefore, during the eccentric phase of movements, the passive elastic components of the muscle–tendon units may store greater strain energy by optimizing joint stiffness. Enhanced performance is produced when this stored energy is released during the propulsive phase, potentiating the demand for force production (Komi, 2003). For instance, increased ankle (Stefanyshyn and Nigg, 1998) and knee (Kuitunen et al., 2002) stiffness have been found with increased running velocity.

Potential sex differences in joint stiffnesses have also been reported (Ford et al., 2010; Schmitz and Shultz, 2010). Males have demonstrated increased hip (Ford et al., 2010; Schmitz and Shultz, 2010), knee, and ankle stiffness (Ford et al., 2010) during drop jump compared to females. The increased joint stiffness in males was attributed to small changes in joint angle combined with increased external joint moment

---

* Corresponding author at: 1801 East Cotati Ave., Department of Kinesiology, Sonoma State University, Rohnert Park, CA 94928, USA.
E-mail address: chuny@sonoma.edu (Y. Chun).

https://doi.org/10.1016/j.jbiomech.2023.111667
Accepted 24 May 2023
Available online 27 May 2023

(Ford et al., 2010; Schmitz and Shultz, 2010). However, sex differences in knee stiffness disappeared when the joint moment was normalized by body mass although females had greater knee joint angular displacement (Ford et al., 2010). Given that joint stiffness is changed by the relationship between joint angle and moment, females possibly have different joint stiffness strategies such as quadriceps dominant recruitment pattern to increase internal knee extension moment for the similar knee joint stiffness (Ford et al., 2010). The influence of sex on joint stiffness has been investigated through the injury risk lens, but not through jump performance lens (Ford et al., 2010; Schmitz and Shultz, 2010). Furthermore, it is unknown whether lower extremity joint stiffnesses are important contributors to the vertical jump.

Sex differences in kinetic variables have been identified along with an increase in countermovement jump height (Ebben et al., 2007; Laffaye et al., 2014; McMahon et al., 2017; Rice et al., 2016; Riggs and Sheppard, 2009; Rubio-Arias et al., 2017). Males have demonstrated increased eccentric and concentric impulse (McMahon et al., 2017; Rice et al., 2016), rate of force development (Laffaye et al., 2014; Rice et al., 2016; Riggs and Sheppard, 2009), and peak power during the concentric phase (McMahon et al., 2017; Riggs and Sheppard, 2009; Rubio-Arias et al., 2017) to achieve a higher jump height. Thus, males are likely to achieve increased jump performance utilizing greater force production during reduced duration than females. Although increased knee and ankle stiffness were observed in drop jumps when contact time was intentionally reduced (Arampatzis et al., 2001), the relationship between jump performance and joint stiffness was not investigated.

The potential sex differences in the relationship between joint stiffness and jump performance has not been established in the literature. Therefore, the purpose of the present study was to examine sex differences in lower extremity joint stiffness during vertical drop jump performance. A secondary purpose was to examine the relationship between joint stiffness and jump performance within sex groups. We hypothesized that males would have greater lower extremity joint stiffness during the loading phase, jump height, and net jump impulse as compared to females. We also hypothesized that the females would have different joint stiffness predictors of jump height compared to males.

2. Methods

The study was approved by the University Institutional Review Board and all participants signed the informed consent prior to participation. Thirty healthy and active college students participated in this study. Participants were engaged in physical activities (at least 30 min with moderate-intensity for 5 days/week or at least 20 min with vigorous-intensity for 3 days/week), self-reported good health (i.e., no current injury or recent history of surgery on their lower extremity, pelvis, and lower back). Individuals were excluded if they are limited to vigorous physical activities due to the pain. The dominant leg was identified by their preferred leg to kick a ball (Weinhandl et al., 2015) for the analysis.

Participants performed a 5-minute self-selected warm-up. Participants wore spandex shorts and were instrumented with a full-body cluster-based marker set using passive reflective markers. The clusters were attached to thigh and shank with elastic wraps (SuperWrap, fabrifoam®, Applied Technology International, Ltd., Exton, PA, USA). Individual reflective markers were attached to feet, malleoli, epicondyles of femur, Anterior Superior Iliac Spine (ASIS) and Posterior Superior Iliac Spine (PSIS), upper-limbs, and trunk with double-sided tape and athletic tape.

Participants performed two practice trials at 30 (Padua et al., 2011) and 60 cm boxes (Arampatzis et al., 2001; Walsh et al., 2004) and then completed 15 trials of a drop jump at each box. The box was located at a horizontal distance equal to half of the participant's height from the center of two force platforms. Participants were instructed to drop off from the box without jumping and to land with one foot on each force platform (Padua et al., 2009) and vertically jump as soon as contacting the ground. A minimum of a 30-second rest (longer if needed) between trials was provided. If participants jumped up from the box or landed off the force platforms, the trial was deemed not valid and repeated. To reduce the effects of fatigue on condition, the order of boxes was counterbalanced across participants.

The drop jump trials were captured at 250 Hz using 8 infrared cameras (VANTAGE 5, Vicon Motion System Ltd., Oxford, UK). Two embedded force platforms (OR6-6, AMTI, Watertown, MA, USA) were synchronized with the motion capture system (NEXUS 2.6, Vicon Motion System Ltd., Oxford, UK) and used to collect GRF data at 1000 Hz. To filter marker trajectory and GRF data, C3D files of each trial were imported to MATLAB (MATLAB 2019b, MathWorks, Natick, MA, USA). Power spectral density analyses were performed to select the optimal cut-off frequencies (the minimum frequency that maintained 99 % of the originals). The determined optimal cut-off frequency ranged from 6 to 15 Hz for marker trajectories and 48–95 Hz for GRF data. These cut-off frequencies were used to lowpass filter each marker trajectory and GRF data with 2nd order Butterworth filter (Kristianslund et al., 2012). Visual 3D Professional (C-Motion, Inc., Germantown, MA, USA) was utilized to model a CODA pelvis using PSIS and ASIS markers and define the hip joint centers based on the markers on ASIS (Bell et al., 1990, 1989). Ankle and knee joint centers were estimated by the mid-points between markers on malleoli and epicondyles, respectively. Based on the defined joint centers and GRF data, lower extremity joint angles and external moments were calculated using a Cardan (X-Y-Z) rotation sequence. The direction of rotation of joint angles and external moments were matched across limbs. The positive values indicate hip flexion, knee flexion, and ankle dorsiflexion in the sagittal plane and hip adduction, knee adduction, and ankle inversion in the frontal plane.

Kinematics and kinetics data were extracted and imported into MATLAB for analyses. Ground contact period was defined as the period from the initial contact (IC) to toe-off (TO) determined by vGRF threshold set as 20 N (Krosshaug et al., 2016) after dropping off from the box (Ford et al., 2003). The ground contact period was subdivided into loading (from IC to the first peak vGRF [PvGRF]), absorption (from PvGRF to the lowest vertical position of the COM [COM_{min}]; Harry et al., 2018) and propulsion phases (from COM_{min} to TO).

Joint angle and moment of each trial during the ground contact period were interpolated to 101 data points (i.e., 0–100 %) and then averaged for each data point. The vGRF and vertical position of COM were interpolated and averaged to divide the landing period into the loading and absorption phase for joint stiffness. Using the joint angle and moment for each subphase with the 2nd order polynomial regression model (Chun et al., 2022), the slopes of each data point were calculated and averaged throughout each phase to indicate joint stiffness ($N{\cdot}m{\cdot}kg^{-1}{\cdot}^{\circ -1}$). The coefficients of determination (r^2) were calculated for each model and phase to identify how well the equation represents the data (Arampatzis et al., 2001; Ford et al., 2010; Padua et al., 2005).

Other dependent variables were the duration of the subphases [loading phase (t_1), absorption phase (t_2), propulsive phase (t_3)], PvGRF (GRF_1), and vGRF at COM_{min} (GRF_2). The net jump impulse was identified by the area of the curve where vGRF exceeds the participant's body weight during the propulsion phase (Fig. 1; Kirby et al., 2011; Mizuguchi, 2012). GRF and the net jump impulse were normalized by body weight and body mass, respectively. Jump height was calculated as the vertical displacement of the COM (i.e., TO – the highest vertical position).

Statistical analyses were performed using R software (R Core Team, 2020). Multiple independent *t*-tests were used to compare potential group differences for participants' height, body mass, age, and the number of trials needed to complete 15 trials for each box between males and females. Multiple mixed 2-way ANOVAs were performed with two independent variables: box height (within-factors) and sex (between-factors). All dependent variables were joint stiffnesses, associated r^2 during the loading and absorption phases, and all other

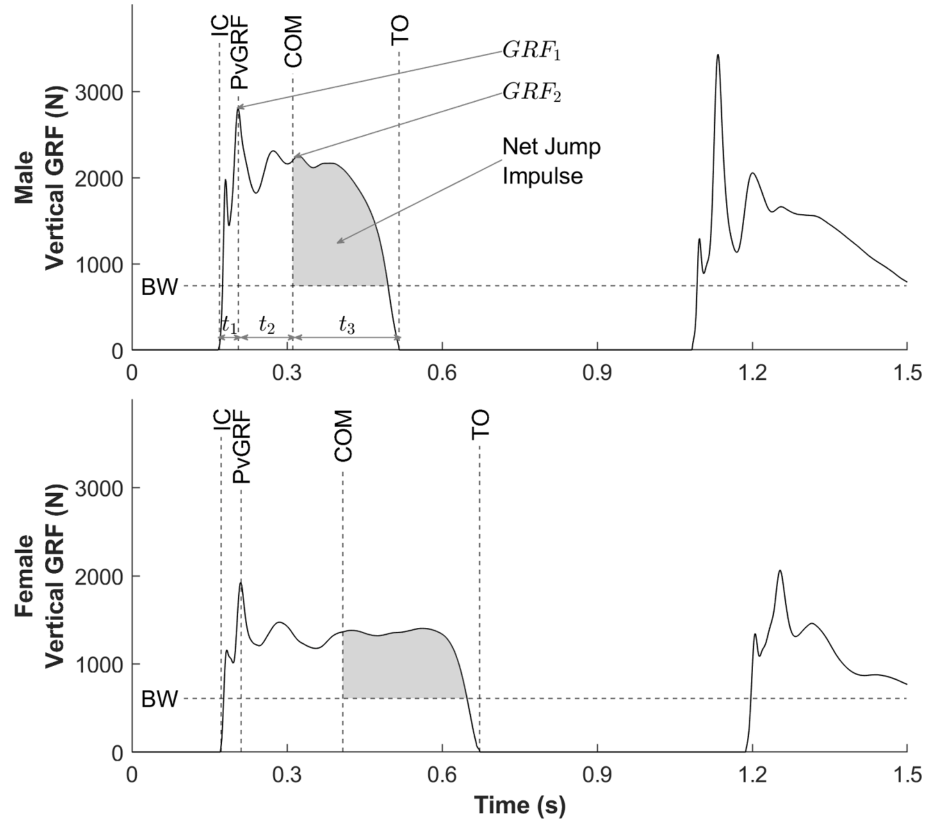

Fig. 1. Example of the vGRF-time curve for each male and female. BW: Body weight, IC: Initial contact, PvGRF: Peak vertical ground reaction force, COM: Lowest COM position, TO: Toe-off, t_1: Time window of the loading phase, t_2: Time window of the absorption phase, t_3: Time window of the propulsive phase, GRF_1: PvGRF, GRF_2: vGRF at the center of mass located the lowest vertical position.

spatiotemporal and kinetic variables. To indicate the magnitude of differences, partial omega squared (ω^2: small = 0.01, medium = 0.06, large = 0.14) was also calculated (Kotrlik et al., 2011). If a significant interaction was found, post-hoc analyses were performed with Tukey's HSD for pairwise comparisons. Multiple regressions for each group (i.e., males and females) were performed to identify the relationship between jump height and joint stiffness. The regression models were calculated without the inclusion of jump impulse due to the known relationship between the two variables. Alpha for all statistical analyses was set at 0.05.

3. Results

Males (ht = 1.82 ± 0.04 m, BM = 82.4 ± 12.1 kg) had significantly greater height (ht; $t(28) = 4.330$, $p < .001$) and body mass (BM; $t(28) = 4.204$, $p < .001$) than females (ht = 1.71 ± 0.09 m, BM = 64.5 ± 11.2 kg). No significant differences in age (M = 25.8 ± 6.6 yrs, F = 25.2 ± 9.2 yrs) or the number of trials to complete tasks between sexes (30 cm: M = 19.4 ± 2.8, F = 18.5 ± 2.3; 60 cm: M = 18.3 ± 2.7, F = 17.7 ± 2.3) were found.

No significant interaction and sex main effects were observed in the joint stiffness and r^2 of all joints during the loading phase. The hip stiffness ($F(1,28) = 28.077$, $p < .001$, $\omega^2 = 0.203$; 30 cm < 60 cm) was significantly increased at 30 cm box height during the loading phase but reduced knee stiffness ($F(1,28) = 31.313$, $p < .001$, $\omega^2 = 0.278$) as compared to 60 cm box (Table 1). The 60 cm box indicated significantly increased r^2 of all joints regardless of sex (Hip: $F(1,28) = 14.554$, $p < .001$, $\omega^2 = 0.179$; Knee: $F(1,28) = 7.449$, $p = .011$, $\omega^2 = 0.075$; Ankle: $F(1,28) = 4.609$, $p = .041$, $\omega^2 = 0.013$).

During the absorption phase, significant interaction effects were observed in the hip stiffness ($F(1,28) = 6.364$, $p = .018$, $\omega^2 = 0.015$), r^2 of the hip ($F(1,28) = 5.035$, $p = .033$, $\omega^2 = 0.021$), and r^2 of the knee ($F(1,28) = 6.724$, $p = .015$, $\omega^2 = 0.019$; Table 2 and Fig. 2). In the post-hoc analyses, males had increased hip stiffness at both 30 and 60 cm box

Table 1
Average joint stiffnesses and r^2 during the loading phase.

	Male		–	Female		–	Sex		–	Box	
	30 cm	60 cm		30 cm	60 cm		Male	Female		30 cm	60 cm
Stiffness ($N{\cdot}m{\cdot}kg^{-1}{\cdot}^{\circ -1}$)											
Hip†	0.152 (0.490)	−0.778 (1.056)		−0.101 (1.426)	−1.984 (2.092)		−0.313 (0.937)	−1.042 (2.003)		0.025 (1.056)	−1.381 (1.740)
Knee†	0.079 (0.081)	0.256 (0.247)		0.092 (0.123)	0.412 (0.280)		0.168 (0.202)	0.252 (0.268)		0.086 (0.102)	0.334 (0.272)
Ankle	0.047 (0.056)	0.063 (0.025)		0.003 (0.156)	0.069 (0.030)		0.055 (0.043)	0.036 (0.116)		0.025 (0.118)	0.066 (0.027)
r^2											
Hip†	0.819 (0.190)	0.93.2 (0.085)		0.826 (0.187)	0.984 (0.039)		0.876 (0.155)	0.903 (0.154)		0.822 (0.185)	0.956 (0.070)
Knee†	0.814 (0.202)	0.865 (0.245)		0.732 (0.268)	0.942 (0.126)		0.839 (0.222)	0.837 (0.232)		0.773 (0.237)	0.903 (0.195)
Ankle†	0.935 (0.136)	0.980 (0.025)		0.872 (0.252)	0.923 (0.242)		0.958 (0.099)	0.897 (0.244)		0.903 (0.201)	0.952 (0.171)

Notes. † indicates a significant main effect for box height.

Table 2

Average joint stiffnesses and r^2 during the absorption phase.

	Male		Female		Sex		Box	
	30 cm	60 cm	30 cm	60 cm	Male	Female	30 cm	60 cm
Stiffness ($N \cdot m \cdot kg^{-1} \cdot {}^{\circ -1}$)								
Hip*,‡	0.038 (0.014)	0.040 (0.014)	0.029 (0.008)	0.025 (0.008)	0.039 (0.014)	0.027 (0.008)	0.033 (0.012)	0.033 (0.014)
Knee†	0.025 (0.014)	0.019 (0.016)	0.015 (0.017)	0.010 (0.016)	0.022 (0.015)	0.013 (0.016)	0.020 (0.016)	0.015 (0.016)
Ankle†	0.018 (0.016)	0.010 (0.017)	0.007 (0.016)	0.000 (0.018)	0.014 (0.017)	0.003 (0.017)	0.013 (0.017)	0.005 (0.018)
r^2								
Hip*,†,‡	0.774 (0.104)	0.667 (0.169)	0.635 (0.193)	0.413 (0.222)	0.721 (0.148)	0.524 (0.233)	0.705 (0.168)	0.540 (0.233)
Knee*,†,‡	0.860 (0.125)	0.754 (0.157)	0.707 (0.156)	0.512 (0.154)	0.807 (0.150)	0.610 (0.182)	0.784 (0.159)	0.633 (0.196)
Ankle†	0.431 (0.292)	0.601 (0.298)	0.408 (0.247)	0.567 (0.153)	0.516 (0.303)	0.488 (0.217)	0.420 (0.266)	0.584 (0.234)

Notes. * Indicates a significant main effect for sex. † indicates a significant main effect for box height. ‡ indicates a significant interaction effect between sex and box height.

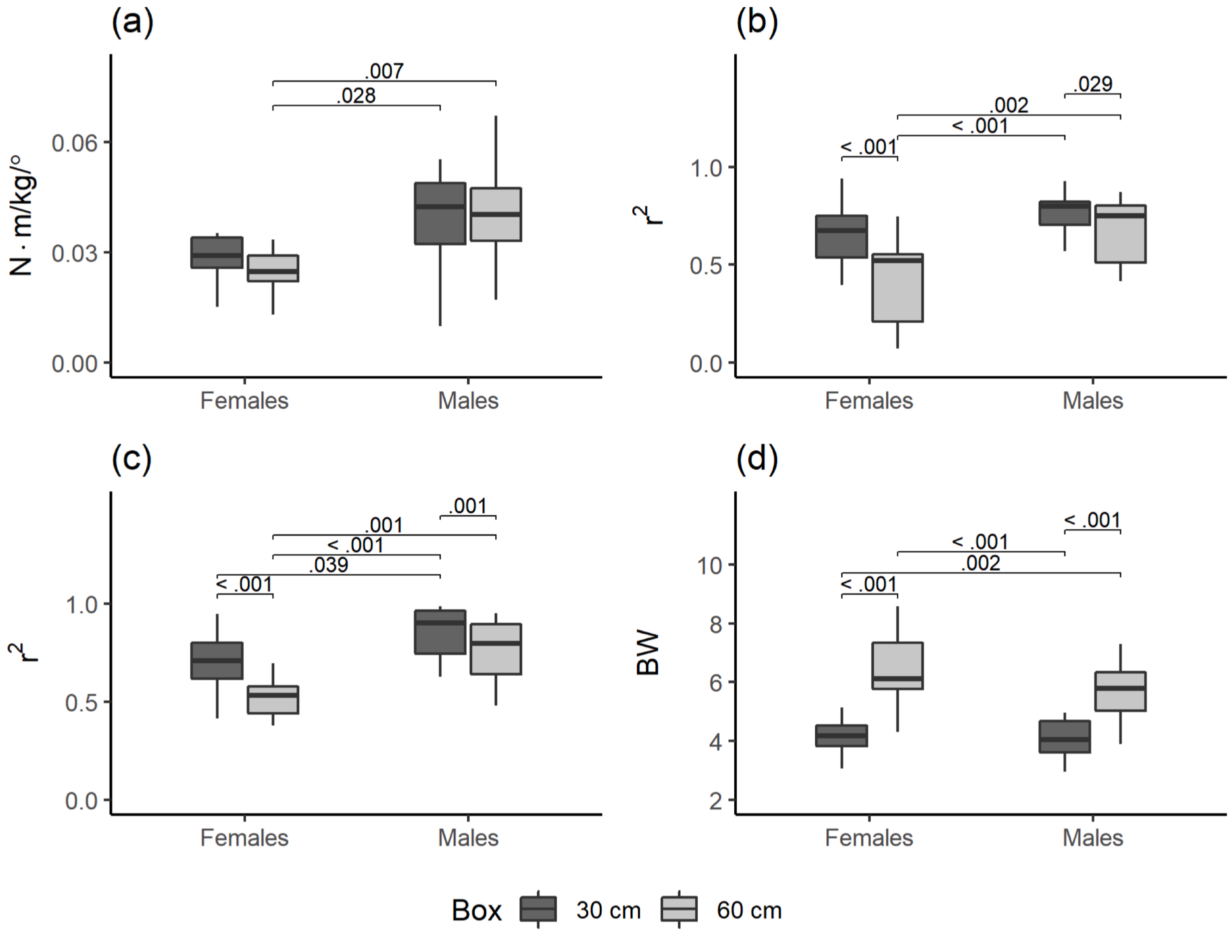

Fig. 2. Box plots of the variables indicating significant interaction effects between box and sex. (a) Hip stiffness during the absorption phase, (b) r^2 of the hip joint during the absorption phase, (c) r^2 of the knee joint during the absorption phase, and (d) peak vertical ground reaction force (GRF_1). Numbers on brackets indicate significant *p*-values of each comparison in post-hoc analyses.

than females at 60 cm (males at 30 cm vs. female at 60 cm: $t(33.1) = -2.959$, $p = 0.028$; males at 60 cm vs. females at 60 cm: $t(33.1) = -3.517$, $p = 0.007$). The r^2 of the hip of females at 60 cm during the absorption phase was significantly reduced compared to females at 30 cm ($t(28) = -6.148$, $p < .001$), males at 30 cm ($t(38.1) = -5.590$, $p < .001$) and 60 cm ($t(38.1) = -3.925$, $p = .002$). Females at 60 cm showed reduced r^2 of the knee compared to all other conditions (females at 30 cm: $t(28) = -8.026$, $p < .001$; males at 30 cm: $t(34.1) = -6.392$, $p < .001$; males at 60 cm: $t(34.1) = -4.448$, $p < .001$). Males displayed reduced r^2 of the knee at 60 cm box compared to 30 cm box ($t(28) = -4.358$, $p < .001$). Significant box main effects in knee and ankle stiffness and r^2 of the ankle were observed. Knee ($F(1,28) = 8.259$, $p = .008$, $\omega^2 = 0.028$) and ankle ($F(1,28) = 22.984$, $p < .001$, $\omega^2 = 0.048$) stiffnesses were significantly reduced in the 60 cm box compared to the 30 cm box. The 60 cm box significantly increased r^2 of the ankle ($F(1,28) = 36.700$, $p < .001$, $\omega^2 = 0.094$) as compared to the 30 cm box.

A significant interaction was observed in GRF_1 ($F(1,28) = 8.101$, $p = .008$, $\omega^2 = 0.031$; Table 3 and Fig. 2). Females at 30 cm had significantly reduced GRF_1 as compared to females at 60 cm ($t(28) = -12.556$, $p < .001$) and males drop jumping at 60 cm ($t(36.1) = -4.005$, $p = .002$). Females had significantly increased GRF_1 at 60 cm box compared to males at 30 cm ($t(36.1) = 6.684$, $p < .001$), and males had greater GRF_1 at 60 cm box than 30 cm box ($t(28) = -8.531$, $p < .001$).

Significant sex main effects were found in GRF_2, net jump impulse,

Table 3
Time, vGRF, vertical net impulse, and jump height.

	Male		Female		Sex		Box	
	30 cm	60 cm	30 cm	60 cm	Male	Female	30 cm	60 cm
t_1(s)	0.048 (0.021)	0.045 (0.010)	0.041 (0.012)	0.040 (0.008)	0.046 (0.016)	0.041 (0.010)	0.045 (0.017)	0.042 (0.009)
t_2(s)	0.175 (0.092)	0.184 (0.010)	0.208 (0.071)	0.213 (0.068)	0.180 (0.081)	0.211 (0.068)	0.192 (0.082)	0.199 (0.071)
t_3(s)	0.266 (0.085)	0.273(0.074)	0.310 (0.098)	0.319 (0.100)	0.269 (0.078)	0.315 (0.098)	0.288 (0.093)	0.296 (0.090)
GRF_1 (BW)†,‡	4.103 (0.672)	5.620 (1.038)	4.215 (0.955)	6.448 (1.119)	4.861 (1.155)	5.331 (1.528)	4.159 (0.816)	6.034 (1.141)
GRF_2 (BW) *	2.670 (0.419)	2.624 (0.389)	2.221 (0.616)	2.177 (0.607)	2.647 (0.398)	2.199 (0.602)	2.445 (0.566)	2.400 (0.550)
Net jump Impulse ($N{\cdot}s{\cdot}kg^{-1}$)*	2.938 (0.259)	2.936 (0.279)	2.243 (0.393)	2.251 (0.378)	2.937 (0.264)	2.247 (0.379)	2.591 (0.481)	2.594 (0.477)
Jump Height (m)*	0.339 (0.054)	0.338 (0.056)	0.201 (0.070)	0.202 (0.070)	0.338 (0.054)	0.201 (0.068)	0.270 (0.093)	0.270 (0.093)

Notes. * Indicates a significant main effect for sex. † indicates a significant main effect for box height. ‡ indicates a significant interaction effect between sex and box height. t_1: Duration of the loading phase; t_2: Duration of the absorption phase; t_3: Duration of the propulsive phase; GRF_1: the first peak vGRF; GRF_2: vGRF at COM located at the lowest position.

and jump height (Table 3). Males possessed greater GRF_2 ($F(1,28) = 6.034$, $p = .021$, $\omega^2 = 0.144$), net jump impulse ($F(1,28) = 32.490$, $p < .001$, $\omega^2 = 0.512$), and jump height ($F(1,28) = 36.320$, $p < .001$, $\omega^2 = 0.541$) than females.

The multiple regression model was significant for females ($p < .001$), but not for males ($p = 0.609$). The hip and knee stiffness during the loading phase were included in female's model as significant predictors to jump height (Table 4).

4. Discussion

Our study had two purposes: 1) to investigate potential sex differences in lower extremity joint stiffness during drop jump; and 2) to identify the relationship between joint stiffness and jump performance for each sex. Our first hypothesis of sex differences in stiffness was only partially accepted with males possessing greater hip stiffness during the absorption phase compared to females. Males had greater hip stiffness at both boxes than females at 60 cm. The major findings were that joint stiffness was only a predictor of drop jump height for females. The only stiffness to enter as jump height predictive equation for females were hip and knee during the loading phase. Further analyses led to box height differences regardless of sex. During the loading phase, the hip was more compliant whereas the knee was stiffer when drop jumping from the 60 cm box. During the absorption phase, both the knee and ankle were more compliant with an increased box height.

The lack of sex differences in joint stiffness during the loading phase was a surprise. This result may be attributed to the lack of differences in the external joint moments normalized by body mass. Fig. 3 indicates similar approaches to the initial contact and loading response across groups. Specifically, both males and females tend to have delayed peak joint moments (i.e., peak moments appeared not during the loading phase but during the absorption or propulsive phases). Given that the loading phase took about 40 ms in average (t_1 in Table 3), it could be considered that males and females may not be able to develop sufficient muscle forces (Peñailillo et al., 2015) to overcome the external moments during the loading phase due to the short period of the phase. Muscles could be preactivated before landing to minimize the electromechanical delays as the task of the present study is not an unanticipated task; however, it was reported that the quadriceps pre-activation was not related to knee joint stiffness during the loading phase (Horita et al., 2002). Thus, the loading phase is likely too short to expect different joint stiffness in response to the external load between males and females.

Interestingly, males even possessed a stiffer hip at both 30 and 60 cm boxes than the females at 60 cm box (Fig. 2: a). As seen in Fig. 3, males tend to exhibit greater hip moment throughout the absorption phase, which could make males stiffen hip during the absorption phase. This increased hip external flexion moment in males may reflect efficient muscle force transmission during the complex movement tasks like drop jump (Bojsen-Møller et al., 2005; Schmitz and Shultz, 2010). The increased hip external flexion moment may reflect the residual effects of the males experiencing a greater GRF_2 than the females, with a lack of differences for stiffness across the more distal joints. Males may also demonstrate a greater ability to store greater elastic energy in their hip extensors during the absorption phase and to return it during the propulsive phase. The storing and returning ability combined with the increased GRF_2 may have assisted with the increased net jump impulse in males resulting in a greater jump height.

Further support for different strategies of utilizing joint stiffnesses to achieve maximal jump height are seen in comparing regression models. The female model was the only model found to be significant, with only hip and knee stiffness during the loading phase as predictive variables. The inclusion of the more proximal joints for females is contrary to running performance which connects increased stiffness of the ankle joint to increased run performance (Kuitunen et al., 2002; Stefanyshyn and Nigg, 1998). There are two possible explanations of this contradictory: the difference in the population of the previous studies and the task differences in between running and box jumps. It is suggested that females could have a different strategy of dependence more on proximal joint stiffness unlike males in that these previous studies examined only males. For the task differences, both running and drop jumping required that the individual structures must overcome the braking forces in posterior and vertical directions by modulating joint stiffness components. However, the drop jump imparts a greater vGRF in response to the drop height, requiring greater muscle activation and potentially greater angular displacement of the joints to stop the vertical motion prior to executing the subsequent jumping (DeVita and Skelly, 1992). Females have been found to exhibit greater negative work in knee joint than males (Schmitz and Shultz, 2010). This supports a reliance on the knee for females to increase jump height as demonstrated by the greater

Table 4
Multiple regression models for each male and female.

	Male			Female		
	β	t	p	β	t	p
Intercept	0.309	7.36	<0.001	0.152	3.267	0.003*
Loading						
Hip	0.029	0.82	0.421	0.028	3.036	0.006*
Knee	0.152	0.942	0.356	0.511	0.366	0.029*
Ankle	0.151	0.511	0.614	0.143	1.842	0.078
Absorption						
Hip	−0.625	−0.715	0.482	0.511	0.366	0.718
Knee	1.526	1.386	0.179	1.175	1.085	0.289
Ankle	−0.372	−0.415	0.682	1.498	1.301	0.206
F(6,23)	0.759			7.635		
p	0.609			<0.001*		
adjusted r^2	−0.053			0.579		

Note. * indicates significant regression model and predictors for drop jump height.

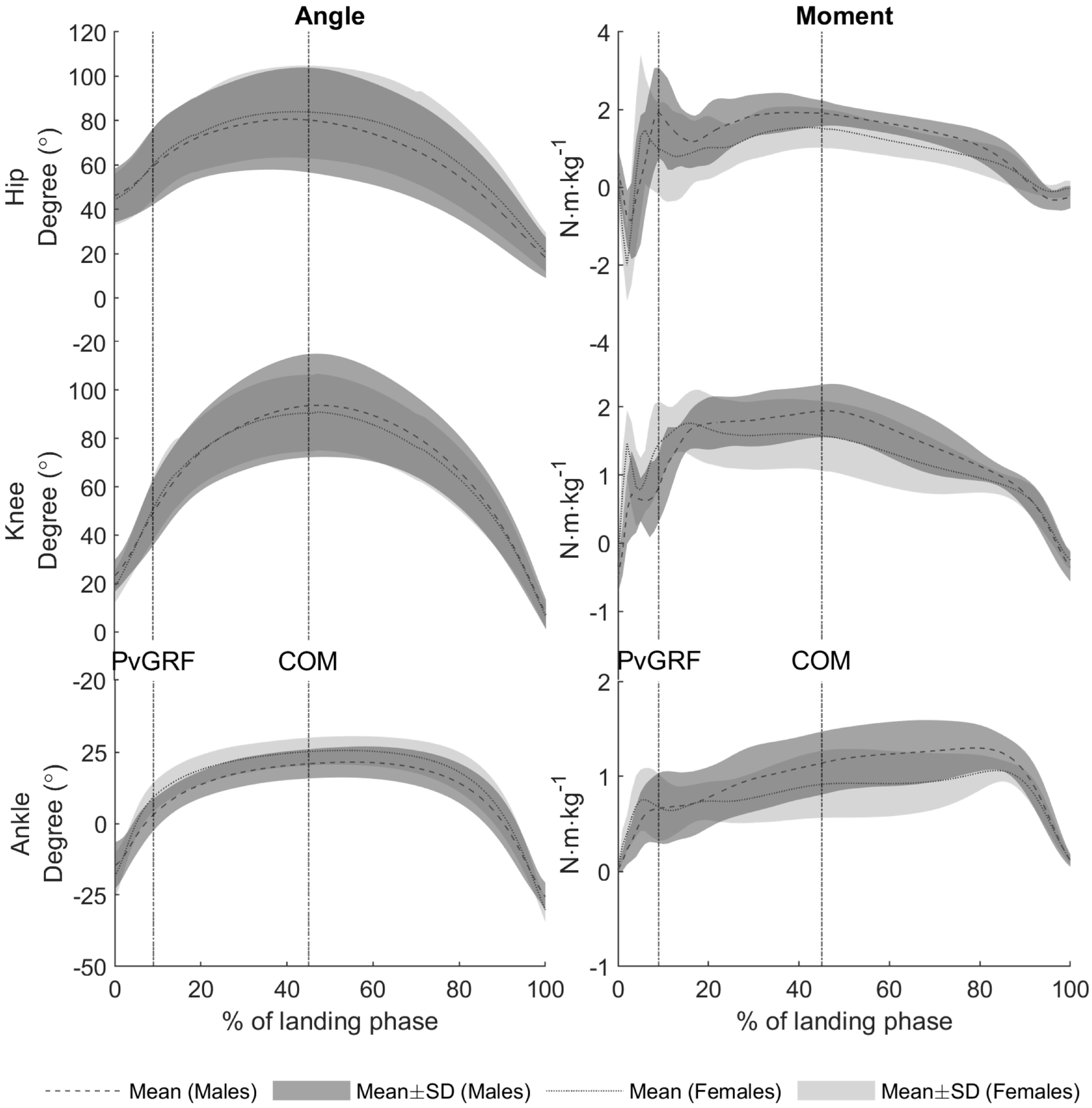

Fig. 3. Sex group mean angles and moments of hip, knee, and ankle joints during the ground contact period. Positive values are joint flexion angle and external flexion moment, and negative values are joint extension angle and external extension moment. PvGRF: Peak vertical ground reaction force; COM: The center of mass located at the lowest position.

coefficient of the knee stiffness in the regression model. Thus, it is possible that females rely more on the stored elastic energy in knee extensor muscle–tendon units during the loading phase to maximize jump height.

Although males had greater hip stiffness during the absorption phase than females at 60 cm, their joint stiffness did not account for jump height. Males have a greater ability to produce torque and power in knee extensors during concentric contraction (Pincivero et al., 2003). Combined with the possibility of the task demand not being as difficult for the taller male population, the males may not have required dependence upon the SSC to achieve jump performance.

In addition to the limited sex differences, box height differences were found. The increased box height caused a reduction in hip stiffness during the loading phase, but increased knee stiffness. The demand on the system due to the direction of the GRF during the loading phase, may increase the role the knee plays in attenuation of the external load given the task (Decker et al., 2003; Yeow et al., 2010). Specifically, the posterior GRF resulted in the hip external extension moment while the hip flexes at the beginning of the loading phase (Fig. 4). This interaction of the joint moment and angle reduced hip stiffness during the loading phase as both the posterior and vertical GRF were increased in response to the increased box height and the horizontal distance to the force platforms. However, the increased knee stiffness was related to the rapid increase of the knee external flexion moment during the loading phase due to the increased GRF by the higher box height. During the absorption phase, the knee and ankle became more compliant at the higher box height in response to reduced moments throughout the phase (Fig. 4). However, it is possible that the increased compliance is attempting to optimize the stiffness of those joints to appropriately engage SSC to effectively utilize the external load, which may also be a strategy to reduce the impact.

While we recruited individuals who were regularly engaging in physical activity, a potential study limitation is the types of exercises. An aerobic endurance exercise (e.g., running, swimming, and cycling) was the main physical activity for 16 out of 30 participants, and 10 of these 16 participants were female. Muscle and tendon properties can be altered by the type of exercises: aerobic endurance training increases type I fibers (Goubel and Marini, 1987) and plyometric training type II muscle fibers (Almeida-Silveira et al., 1994; Goubel and Marini, 1987), which also affect the stiffness of the muscle–tendon unit (Almeida-

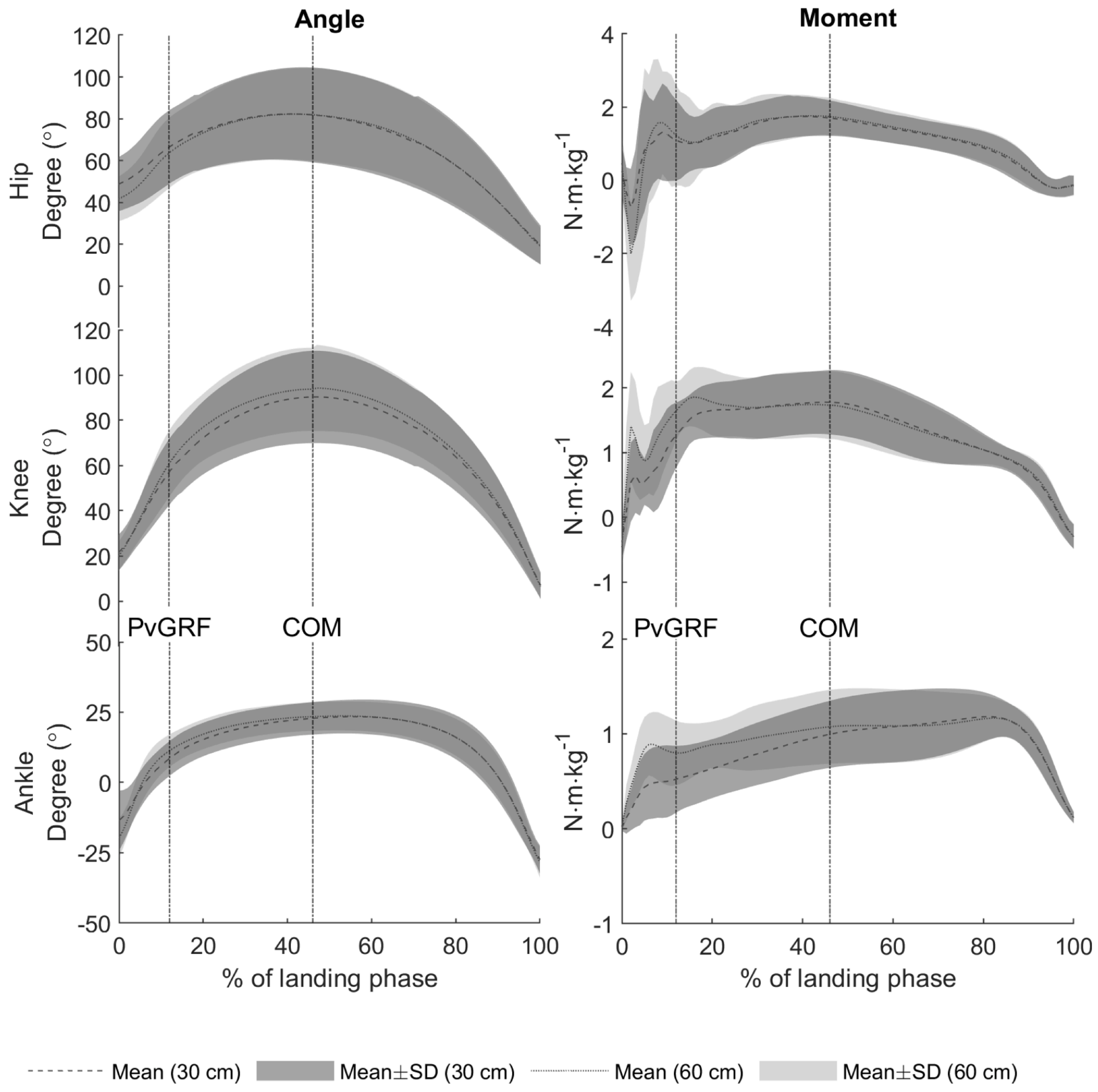

Fig. 4. Box height group mean angles and moments of hip, knee, and ankle joints during the ground contact period. Positive values are joint flexion angle and external flexion moment, and negative values are joint extension angle and external extension moment. PvGRF: Peak vertical ground reaction force; COM: The center of mass located at the lowest position.

Silveira et al., 1994; Fouré et al., 2010; Goubel and Marini, 1987). Thus, the sex difference in joint stiffness, impulse, and jump performance may also encompass the effect of different exercises on these variables due to a greater proportion of participation in aerobic endurance exercises in females than males.

Another potential limitation is the box height and position. Since males had significantly greater height than females in this study, the box heights were relatively higher for females and this could affect females' drop-jump strategies in both box heights. Also, the horizontal position of the boxes in this study is most likely to influence the external joint moment in the sagittal plane. Based on the considerations of the box heights and positions, it would be necessary to examine the joint stiffness strategies during the drop jump from boxes with the same relative heights and minimized horizontal distance. Lastly, 15 repetitions with minimum of 30 s rest might be thought to affect jump performance due to the fatigue. However, it was determined that participants did not have changes in jump height across repetitions in the supplemental analysis. Thus, it is unlikely to induce muscle fatigue in that the jump height was not reduced (Jiménez-Reyes et al., 2019).

In summary, the present study evaluated sex differences in lower extremity joint stiffness using subdivided phases of drop jumps and jump performance. Both males and females did not manipulate their joint stiffness during the loading phase, but males had stiffer hip during the absorption phase than females. It is considered that males focus on utilization of the impact force for the following jump by stiffening hip joints whereas females attenuate the impact force by the compliant hip joints. Using these different joint stiffness strategies, males jumped higher than females. Interestingly, lower extremity joint stiffnesses were only predictors for females in the maximizing drop jump task.

CRediT authorship contribution statement

Youngmin Chun: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Craig P. McGowan:** Conceptualization, Methodology, Validation, Writing – review & editing. **Jeffrey G. Seegmiller:** Conceptualization, Methodology, Validation, Writing – review & editing. **Russell T. Baker:**

Conceptualization, Methodology, Validation, Writing – review & editing. **Joshua P. Bailey:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors appreciate the support of the Human Performance Laboratory members and Department of Movement Sciences students in conducting this study. Lukas Krumpl, M.S., and Nickolai Martonick, Ph. D. candidate, are acknowledged for help in data acquisition.

References

Almeida-Silveira, M.I., Pérot, C., Pousson, M., Goubel, F., 1994. Effects of stretch-shortening cycle training on mechanical properties and fibre type transition in the rat soleus muscle. Pflugers Arch. 427 (3 - 4), 289–294. https://doi.org/10.1007/BF00374536.

Arampatzis, A., Schade, F., Walsh, M., Brüggemann, G.-P., 2001. Influence of leg stiffness and its effect on myodynamic jumping performance. J. Electromyogr. Kinesiol. 11 (5), 355–364. https://doi.org/10.1016/S1050-6411(01)00009-8.

Bell, A.L., Brand, R.A., Pedersen, D.R., 1989. Prediction of hip joint centre location from external landmarks. Hum. Mov. Sci. 8 (1) https://doi.org/10.1016/0167-9457(89)90020-1.

Bell, A.L., Pedersen, D.R., Brand, R.A., 1990. A comparison of the accuracy of several hip center location prediction methods. J. Biomech. 23 (6) https://doi.org/10.1016/0021-9290(90)90054-7.

Blickhan, R., 1989. The spring-mass model for running and hopping. J. Biomech. 22 (11 - 12), 1217–1227. https://doi.org/10.1016/0021-9290(89)90224-8.

Bojsen-Møller, J., Magnusson, S.P., Rasmussen, L.R., Kjaer, M., Aagaard, P., 2005. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. J. Appl. Physiol. 99 (3), 986–994. https://doi.org/10.1152/japplphysiol.01305.2004.

Chun, Y., McGowan, C.P., Kim, J., Bailey, J.P., 2022. Application of polynomial regression model for joint stiffness. Int. J. Exerc. Sci. 15 (1), 1236–1245.

Decker, M.J., Torry, M.R., Wyland, D.J., Sterett, W.I., Richard Steadman, J., 2003. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin. Biomech. 18 (7), 662–669. https://doi.org/10.1016/s0268-0033(03)00090-1.

DeVita, P., Skelly, W.A., 1992. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. Med. Sci. Sports Exerc. 24 (1), 108–115. https://doi.org/10.1249/00005768-199201000-00018.

Ebben, W., Flanagan, E., Jensen, R., 2007. Gender similarities in rate of force development and time to takeoff during the countermovement jump. J Exerc Physiol Online 10, 10–17.

Farley, C.T., Morgenroth, D.C., 1999. Leg stiffness primarily depends on ankle stiffness during human hopping. J. Biomech. 32 (3), 267–273. https://doi.org/10.1016/S0021-9290(98)00170-5.

Ford, K.R., Myer, G.D., Hewett, T.E., 2003. Valgus knee motion during landing in high school female and male basketball players. Med. Sci. Sports Exerc. 35 (10), 1745–1750. https://doi.org/10.1249/01.MSS.0000089346.85744.D9.

Ford, K.R., Myer, G.D., Hewett, T.E., 2010. Longitudinal effects of maturation on lower extremity joint stiffness in adolescent athletes. Am. J. Sports Med. 38 (9), 1829–1837. https://doi.org/10.1177/0363546510367425.

Fouré, A., Nordez, A., Cornu, C., 2010. Plyometric training effects on Achilles tendon stiffness and dissipative properties. J. Appl. Physiol. 109 (3), 849–854. https://doi.org/10.1152/japplphysiol.01150.2009.

Goubel, F., Marini, J.F., 1987. Fibre type transition and stiffness modification of soleus muscle of trained rats. Pflugers Arch. 410 (3), 321–325. https://doi.org/10.1007/BF00580283.

Hamill, J., Knutzen, K.M., Derrick, T.R., 2015. Biomechanical Basis of Human Movement, 4th ed. Lippincott Williams & wilkins, Philadelphia, PA.

Harry, J.R., Barker, L.A., Eggleston, J.D., Dufek, J.S., 2018. Evaluating performance during maximum effort vertical jump landings. J. Appl. Biomech. 34 (5), 403–409. https://doi.org/10.1123/jab.2017-0172.

Horita, T., Komi, P.V., Nicol, C., Kyröläinen, H., 2002. Interaction between pre-landing activities and stiffness regulation of the knee joint musculoskeletal system in the drop jump: Implications to performance. Eur. J. Appl. Physiol. 88 (1 - 2), 76–84. https://doi.org/10.1007/s00421-002-0673-6.

Jiménez-Reyes, P., Pareja-Blanco, F., Cuadrado-Peñafiel, V., Ortega-Becerra, M., Párraga, J., González-Badillo, J.J., 2019. Jump height loss as an indicator of fatigue during sprint training. J. Sports Sci. 37 (9), 1029–1037. https://doi.org/10.1080/02640414.2018.1539445.

Kirby, T.J., McBride, J.M., Haines, T.L., Dayne, A.M., 2011. Relative net vertical impulse determines jumping performance. J. Appl. Biomech. 27 (3), 207–214. https://doi.org/10.1123/jab.27.3.207.

Komi, P.V., 2003. Strength and Power in Sport, second ed. Blackwell Science Ltd, Oxford, UK. doi: 10.1002/9780470757215.

Kotrlik, J., Williams, H., Jabor, K., 2011. Reporting and interpreting effect size in quantitative agricultural education research. J. Agric. Educ. 52 (1), 132–142. https://doi.org/10.5032/jae.2011.01132.

Kristianslund, E., Krosshaug, T., Van den Bogert, A.J., 2012. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. J. Biomech. 45 (4), 666–671. https://doi.org/10.1016/j.jbiomech.2011.12.011.

Krosshaug, T., Steffen, K., Kristianslund, E., Nilstad, A., Mok, K.-M., Myklebust, G., Andersen, T.E., Holme, I., Engebretsen, L., Bahr, R., 2016. The vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players: a prospective cohort study of 710 athletes. Am. J. Sports Med. 44 (4), 874–883. https://doi.org/10.1177/0363546515625048.

Kuitunen, S., Komi, P.V., Kyröläinen, H., 2002. Knee and ankle joint stiffness in sprint running. Med. Sci. Sports Exerc. 34 (1), 166–173. https://doi.org/10.1097/00005768-200201000-00025.

Laffaye, G., Wagner, P.P., Tombleson, T.I.L., 2014. Countermovement jump height: Gender and sport-specific differences in the force-time variables. J. Strength Cond. Res. 28 (4), 1096–1105. https://doi.org/10.1519/JSC.0b013e3182a1db03.

McMahon, J., Rej, S., Comfort, P., 2017. Sex differences in countermovement jump phase characteristics. Sports 5 (1), 8. https://doi.org/10.3390/sports5010008.

Mizuguchi, S., 2012. Net impulse and net impulse characteristics in vertical jumping. Ph. D. Dissertataion, East Tennessee State University.

Morin, J.-B., Dalleau, G., Kyröläinen, H., Jeannin, T., Belli, A., 2005. A simple method for measuring stiffness during running. J. Appl. Biomech. 21 (2), 167–180. https://doi.org/10.1123/jab.21.2.167.

Padua, D.A., Garcia, C.R., Arnold, B.L., Granata, K.P., 2005. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. J. Mot. Behav. 37 (2), 111–125. https://doi.org/10.3200/JMBR.37.2.111-126.

Padua, D.A., Marshall, S.W., Boling, M.C., Thigpen, C.A., Garrett, W.E., Beutler, A.I., 2009. The landing error scoring system (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics the JUMP-ACL study. Am. J. Sports Med. 37 (10), 1996–2002. https://doi.org/10.1177/0363546509343200.

Padua, D.A., Boling, M.C., DiStefano, L.J., Onate, J.A., Beutler, A.I., Marshall, S.W., 2011. Reliability of the landing error scoring system-real time, a clinical assessment tool of jump-landing biomechanics. J. Sport Rehabil. 20 (2), 145–156. https://doi.org/10.1123/jsr.20.2.145.

Peñailillo, L., Blazevich, A., Numazawa, H., Nosaka, K., 2015. Rate of force development as a measure of muscle damage. Scand. J. Med. Sci. Sports 25 (3), 417–427. https://doi.org/10.1111/sms.12241.

Pincivero, D.M., Gandaio, C.B., Ito, Y., 2003. Gender-specific knee extensor torque, flexor torque, and muscle fatigue responses during maximal effort contractions. Eur. J. Appl. Physiol. 89 (2), 134–141. https://doi.org/10.1007/s00421-002-0739-5.

R Core Team, 2020. R: A language and environment for statistical computing.

Rice, P.E., Goodman, C.L., Capps, C.R., Triplett, N.T., Erickson, T.M., McBride, J.M., 2016. Force– and power–time curve comparison during jumping between strength-matched male and female basketball players. Eur. J. Sport Sci. 17 (3), 286–293. https://doi.org/10.1080/17461391.2016.1236840.

Riggs, M.P., Sheppard, J.M., 2009. The relative importance of strength and power qualities to vertical jump height of elite beach volleyball players during the counter-movement and squat jump. J. Hum. Sport Exerc. 4 (3), 221–236. https://doi.org/10.4100/jhse.2009.43.04.

Rubio-Arias, J.Á., Ramos-Campo, D.J., Peña Amaro, J., Esteban, P., Mendizábal, S., Jiménez, J.F., 2017. Gender variability in electromyographic activity, in vivo behaviour of the human gastrocnemius and mechanical capacity during the take-off phase of a countermovement jump. Clin. Physiol. Funct. Imaging 37 (6), 741–749. https://doi.org/10.1111/cpf.12369.

Schmitz, R.J., Shultz, S.J., 2010. Contribution of knee flexor and extensor strength on sex-specific energy absorption and torsional joint stiffness during drop jumping. J. Athl. Train. 45 (5), 445–452. https://doi.org/10.4085/1062-6050-45.5.445.

Stefanyshyn, D.J., Nigg, B.M., 1998. Dynamic angular stiffness of the ankle joint during running and sprinting. J. Appl. Biomech. 14 (3), 292–299. https://doi.org/10.1123/jab.14.3.292.

Walsh, M., Arampatzis, A., Schade, F., Brüggemann, G.-P., 2004. The effect of drop jump starting height and contact time on power, work performed, and moment of force. J. Strength Cond. Res. 18 (3), 561–566. https://doi.org/10.1519/1533-4287(2004)18<561:TEODJS>2.0.CO;2.

Weinhandl, J.T., Irmischer, B.S., Sievert, Z.A., 2015. Sex differences in unilateral landing mechanics from absolute and relative heights. Knee 22 (4), 298–303. https://doi.org/10.1016/j.knee.2015.03.012.

Yeow, C.H., Lee, P.V.S., Goh, J.C.H., 2010. Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. Knee 17 (2), 127–131. https://doi.org/10.1016/j.knee.2009.07.015.