Lower Extremity Joint Stiffness Associated with Drop Jump Performance: Differences in Genders and Athletes

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with a
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Youngmin Chun

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Authorization to Submit Dissertation

This dissertation of Youngmin Chun, submitted for the degree of Doctor of Philosophy with a Major in Education and titled "Lower Extremity Joint Stiffness Associated with Drop Jump Performance Differences in Genders and Athletes," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

A vertical jump task is often performed in combination with a preceding movement which targets activation of the stretch-shortening cycle by a series of eccentric and concentric muscle contractions. Properties of the soft tissues involved can be altered by an athlete's training program, which may enhance their ability to effectively transfer stored elastic energy to maximize performance. Joint stiffness represents the potential ability of an individual joint to resist the external load and contribute the combined lower extremity resistance to an external load. The connection between joint stiffness and jump performance is related to the ability of the structures to store and return of elastic energy through potential manipulation to the angle-moment relationship. Joint stiffness is typically represented by the slope of the line of best-fit obtained by a linear regression model, which indicates the average joint stiffness throughout the entire eccentric or contact phase. However, the linear regression method did not fully represent the curvilinear angle-moment relationship of specific joints during the drop jump task, suggesting that joint stiffness should be calculated using a curvilinear relationship. Furthermore, it was found that the eccentric phase was more accurately represented when the eccentric phase was subdivided into loading and absorption subphases. Therefore, the overall purpose of this dissertation was to investigate the potential relationship between joint stiffness and drop jump performance with the application of a novel method to calculate joint stiffness. To address this purpose, three separate manuscripts were conducted generated from by two independent data collections.

The benefits of utilizing a 2nd order polynomial regression model when calculating lower extremity joint stiffness incorporating subdivided eccentric phases was addressed in the first manuscript. The polynomial regression model had greater goodness-of-fit than the linear regression model for all joint stiffnesses. Differences were found between the two models for hip and knee stiffness during the loading and absorption phases. These results suggest that the polynomial regression model is a more accurate representation of the angle-moment relationship while subdividing the eccentric phase a drop jump into phases.

Sex differences in lower extremity joint stiffness during vertical drop jump performance and potential sex differences between this relationship were the focus for manuscript two. Males had greater hip and ankle stiffness during the loading phase, knee stiffness during the absorption phase, GRF_2, net jump impulse, and jump height than females regardless of box height. The 60 cm box increased all joint stiffnesses during the loading phase, knee and ankle stiffness during the absorption phase, and GRF_1. Hip and knee stiffness during the loading phase predicted jump height of females

whereas the joint stiffness was not related to males' jump height. These results suggest that females have different lower extremity joint stiffness strategies than males to achieve the drop jump.

The primary purpose of the final study was to examine differences in jump performance and joint stiffness between groups of female collegiate athletes (Basketball/Volleyball: BV, Dancers: DAN, Soccer: SOC). A secondary purpose was to identify the relationship between drop jump performance and both joint stiffness and isokinetic strength. The BV group had significantly greater jump height and jump impulse with reduced hip joint stiffness during the loading phase than the DAN group. No differences in isokinetic strength were observed between groups. Hip concentric and knee eccentric extension peak torque were significant independent variables within the overall regression model ($p < .05$, adjusted $r^2 = 0.196$). The individual group regression models included different stiffness and isokinetic variables as predictors. This study supported the hypothesis that female athletes may achieve their max jump height through different strategies based on predictors of each regression model. These differences may be related to the sport specific training and adaptations due to the demands each sport has.

In conclusion, these findings suggest that while testing lower extremity joint stiffness, the eccentric phase of the landing task should be divided into sub phases with a 2^{nd} order polynomial stiffness calculation. Furthermore, predictors for jump height during a drop jump task are different not only across sex, but within the female population with respect to their sport and training history. The goals for each individual athlete may determine the strategy by which they utilize the stretch shortening cycles of the muscle-tendon units. It is however important to note that the task performed may not have a direct implication for performance within each sport.

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Dedication

First and foremost, I dedicate my dissertation to my biggest supporter, closest friend, and wife, Jinah Kim. She sacrificed everything to make me able to solely focus on the dissertation work. I will always appreciate and keep it in my mind.

I also dedicate this dissertation work to my parents, Soonmi Lee and Sang Bog Kim, who have supported and encouraged me to finish the dissertation.

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Chapter 1: Introduction

The vertical jump is one of the crucial movement patterns in many sports and can be performed using a variety of techniques. Although techniques and goals of the jump are different across sports, each utilizes a loading period incorporating the stretch-shortening cycle (SSC) (Bobbert et al., 1996; Kawakami et al., 2002; Komi, 2003; Kubo et al., 2007). The engagement of the SSC enhances jumping performance versus a static jump (Bobbert et al., 1987a, 1996; Kawakami et al., 2002; Kubo et al., 2007) by storing strain energy within the musculoskeletal structures. The SSC combines the storage capacity during the eccentric phase to assist in force transfer during the concentric phase of the movement pattern. When muscles are actively stretched during the downward movement of the center of mass (COM) (McBride et al., 2008), the muscle-tendon unit can store elastic energy like a spring. The stored energy can be then released, aiding propulsion of the body vertically with reduced time delay allowed between eccentric and concentric contraction (Komi, 2003).

Hill's muscle model demonstrates the theoretical relationship between contractile components and passive components in the muscle-tendon unit to transmit force. The muscle-tendon units have two general passive elastic components, parallel elastic components (PEC) and series elastic components (SEC). Within these passive elastic structures, elastic energy can be stored due to the stretching of such structures. Since muscles and PEC are more compliant than SEC, most deformation occurs in muscles and PEC when passive stretching at resting condition (Turner & Jeffreys, 2010). On the other hand, when muscles are actively stretched, the stiffness of muscles become greater than tendons (Turner & Jeffreys, 2010). So, the majority of elastic energy can be therefore stored to tendons rather than PEC (Kawakami et al., 2002; Zatsiorsky, 1997). There is another SEC, titin, to contribute to storing elastic energy during the eccentric contraction. Titin has been considered to increase muscle force during eccentric contraction (Herzog, 2018). The mechanism of increased muscle force by eccentric contraction is binding with calcium ion and actin. Specifically, the increased force is required to lengthen muscles as titin reduces its length that can be stretched out by binding with actin filament (Herzog, 2018). Thus, titin could also store elastic energy during eccentric contraction.

The structural and functional properties of the muscle-tendon unit can be altered by the loading parameters inherent to a physical training program. Plyometric training has increased the proportion of type II muscle fibers (Almeida-Silveira et al., 1994) and Achilles tendon stiffness (Fouré et al., 2010). Conversely, aerobic training has increased the percentage of type I fibers without changes in the tendon stiffness (Almeida-Silveira et al., 1994). Increased type II fibers can improve the force production capabilities of the contractile components of the muscle. Additionally, increased type II fibers induced by the plyometric training may increase recoil capacity of the tendons during eccentric contraction combined with increased Achilles tendon stiffness. Thus, it is expected that the type of sport training an athlete engages in effects the amount of elastic energy stored in the tendon relating to performance capabilities.

Leg or vertical stiffness models have been used to represent an athlete's ability to adjust the structure and function of the lower extremity to modulate the effects of an external load on performance. These stiffness models use relationships between the vertical displacement of the COM (Arampatzis et al., 2001; Morin et al., 2005; Padua et al., 2005) or changes in leg length (Morin et al., 2005) with vertical ground reaction force (vGRF) represented as the spring-mass model. A limitation with using leg or vertical stiffness is that they simplify the entire lower extremity into a linear spring as representation of resistance to the overall external load. As an alternative, joint stiffness illustrates the ability of each joint to modulate its response to the joint specific external load (torque or moment) using the torsional spring model (Farley & Morgenroth, 1999; Ford et al., 2010; Horita et al., 2002; Stefanyshyn & Nigg, 1998).

Muscles that cross a specific joint have an ability to affect joint stiffness during drop jump through contraction. Pre-activation of skeletal muscle, anticipatory activation before event, reduces the electromechanical delay by facilitating quicker peak force production after contacting the ground (Hamill et al., 2015) and could increase ability to stiffen joint during a task (Arampatzis et al., 2001). Increased joint stiffness during a drop jump relies upon concentric activation of skeletal muscle going through eccentric muscle action, engaging both concentric muscle action and the passive components. Drop jumps require a greater amount of eccentric muscle activation versus a countermovement jump to overcome downward momentum (McBride et al., 2008). The potential relationship between joint stiffness and performance of sports-related movements has been investigated (Arampatzis et al., 2001; Farley & Morgenroth, 1999; Stefanyshyn & Nigg, 1998). During running, ankle joint is stiffer during sprinting speeds as compared to slower running speeds (Stefanyshyn & Nigg, 1998). During a hopping task, athletes augmented ankle and knee joint stiffness to achieve an increased hopping height (Farley & Morgenroth, 1999). Increases in ankle and knee joint stiffness were observed in combination with decreased ground contact time during drop jump (Arampatzis et al., 2001). This combination in stiffness adjustments with reduced contact time, may illustrate a relationship between SSC and increased joint stiffness enhancing jump performance. However, this relationship between joint stiffness and drop jump performance is still unknown.

Individual structures of the human body are viscoelastic and respond differently to loads dependent upon structure length and rate of loading. Currently, joint stiffness is often calculated over the entire phase of an activity, the stance phase in running and sprinting (Stefanyshyn & Nigg, 1998) and the eccentric phase of hopping and drop jump (Arampatzis et al., 2001; Farley & Morgenroth, 1999). Using critical events of the activity, joint stiffness may be more useful representing smaller subphases of the eccentric portion of the drop jump when the structures are loaded to a differing degree. During the drop jump, sub-phases have been identified using the appearance of peak vGRF (Bates et al., 2013; Bobbert et al., 1987b, 1987a) and when heel contact occurs immediately after ground contact (Bobbert et al., 1987b). The period of time before the peak vGRF can be thought as a phase at which external load is applied to the body, and each joint seems to directly resist the external force following this phase. Following this phase, lower extremity muscles is eccentrically activated to absorb the external load and store elastic energy until the COM located at the lowest position. This suggests the joint stiffness should be calculated in subdivided phases of the eccentric phase of drop landing in that the stiffness may be altered before and after the peak vGRF.

The overall theme of this dissertation is an investigation into the potential relationship between joint stiffness and drop jump performance with application of a novel method to calculate joint stiffness. This theme is comprised of three specific purposes, comprising two specific data collections: 1) to investigate the benefits of a 2nd order polynomial regression model to calculate joint stiffness for subdivided eccentric phases as compared to a linear model; 2) to examine potential gender difference in the relationship between jump performance and joint stiffness in healthy and active individuals; and 3) to investigate differences in joint stiffness and jump performance and its relationships between female athletes of different physical sport demands.

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Chapter 2: Application of Polynomial Regression Model for Joint Stiffness

Abstract

Joint stiffness is often used to characterize leg properties during athletic and other activities. However, the joint angle-moment relationship is rarely linear. Thus, the purpose of this analysis was to investigate the benefits of utilizing a 2nd order polynomial regression (quadratic) model as compared to the linear model when calculating lower extremity joint stiffness incorporating subdivided eccentric phases. Thirty healthy and active college students performed 15 drop jumps from a 30-cm platform. The eccentric phase was identified as the time from initial foot contact (IC) to the lowest vertical position of the center of mass and subdivided into the loading and absorption phases, separated by the peak vertical ground reaction force. Lower extremity joint stiffnesses (hip, knee, and ankle) for the loading and absorption phases were calculated using a linear and quadratic model. Multiple 2 by 2 repeated measures ANOVAs were performed. In the post-hoc analyses, the quadratic model had greater goodness-of-fit (r^2 and RMSE) than the linear model ($p < .05$) for all joints. The quadratic model revealed differences between the loading and absorption phases for both hip ($p = .001$) and knee stiffness ($p < .001$). These results suggest that the quadratic model is more representative of the angle-moment relationship while subdividing the eccentric phase a drop jump into phases.

Introduction

Lower extremity stiffness is an effective measure to relate load and displacement characteristics in sport-related activities to evaluate performance (1,17) and identify potential injury risk (5,14,16). Stiffness of the lower extremity can be reported as leg stiffness, representing the lower extremity as a spring-mass model (1,2,12,14), or by investigating the stiffness of each joint independently (1,5,16,17). Leg stiffness reflects the ability of all the lower extremity structures to resist the vertical displacement of the center of mass (COM) with respect to the vertical ground reaction force (vGRF) (1,12,14) whereas joint stiffness identifies joint-specific responses to loads (4,5,16).

A commonly used mathematical model to estimate joint stiffness is a linear regression (linear) model using the angle-moment relationship (1,5,16,17). This linear model has commonly been used to calculate joint stiffness and reported high coefficients of determination (r^2) (5,16,17). However, in many cases, the linear model fails to represent the curvilinear and varied relationship of the joint angle-moment. This is demonstrated through hip stiffness during a drop jump, as the external hip moment may decrease at the beginning of the landing phase and then increase until the end of the landing phase. This moment is coupled with a hip angle continuously increasing during the phase (5,16), which causes a curvilinear relationship between joint angle and moment. The line of best fit obtained by the linear model does not accurately represent this curvilinear relationship. The error in the stiffness model may be magnified as the contact time decreases (1).

Moreover, calculating joint stiffness as a single value may also overlook time-varying changes in the angle-moment relationship. For example, a linear model has been utilized to calculate joint stiffness for the entire ground contact period or the eccentric phase during running (17) or drop jumps (5). However, the mechanical property of the joint may be over- or underestimated by a single value of joint stiffness in that each joint's contribution to absorb the kinetic energy during subdivided eccentric phases may differ (7). Thus, calculating joint stiffness for subdivided eccentric phases would provide a better understanding of changes in the mechanical property of joints.

Thus, this study investigated a novel method to more accurately represent the joint angle-moment curvilinear relationship through calculating joint stiffness using the 2nd order polynomial regression (quadratic) model with subdivided eccentric phase. The purpose of this analysis was to investigate the benefits of a 2^{nd} order polynomial regression (quadratic) model to calculate joint stiffness for subdivided eccentric phases as compared to a linear model. We hypothesized that the quadratic model would more accurately indicate best-fit lines in angle-moment relationships than a linear model and would more accurately detect changes in joint stiffness by the tangent slopes.

Methods

Participants

All participants in this study were considered physically active and healthy individuals who are regularly engaged in physical activities at least 30 minutes with moderate-intensity for 5 days per week or at least 20 minutes with vigorous-intensity for 3 days per week (8). Also, they were free from lower extremity injuries within the past year and had no history of surgery to the lower extremity, pelvis, and low back. The data for this analysis were taken from a larger study protocol that was approved by the university institutional review board and all participants gave written consent before participation. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (13).

Protocol

The dominant limb was identified as the leg they use to kick a ball and then used for analysis. Participants performed a self-selected warm-up for at least 5 minutes, and then a customized full-body marker set was applied to bony landmarks for each segment. Four clusters were used to track thigh and shank segments.

Participants performed drop vertical jumps from a 30-cm platform. The platform was positioned at the distance equal to half of the participant's height away from two embedded force platforms. To perform the drop jump, participants were instructed to stand on the edge of the platform and drop off without jumping up while landing with one foot on each force platform (15). They were then instructed to perform a maximal vertical jump immediately upon contacting the ground. Two practice trials were given and then 15 good trials (i.e., both feet on the center of platforms) were collected.

The drop vertical jump trials were captured using a 3-D motion capture system with 8 infrared cameras (VANTAGE 5, Vicon Motion System Ltd., Oxford, UK) and two embedded force platforms (OR6-6, AMTI, Watertown, MA, USA). The motion capture and ground reaction force (GRF) data were collected at 250 Hz and 1000 Hz, respectively. A power spectral density analysis was performed to determine the cut-off frequency for filtering using data from the lower extremity markers and a customized MATLAB script (MATLAB 2019b, MathWorks, Natick, MA, USA). An optimal cut-off frequency was determined to be the frequency that retained 99% of the marker trajectory signals. Both marker trajectory and GRF data were lowpass filtered at the optimal cut-off frequency of 11 Hz, using a 2nd order Butterworth filter (10). The filtered data were transported to Visual3D (Visual3D v6 Professional, C-Motion, Inc., Germantown, MA, USA) to calculate lower extremity joint angles, external moments, and COM of the body. The external joint moments were normalized to body mass ($N \cdot m \cdot kg^{-1}$). The direction of rotation of lower extremity joint angles and external moments were matched, with positive values indicating hip flexion, knee flexion, and ankle dorsiflexion.

Initial foot contact (IC) was identified using a vGRF threshold of 20 N (10,11). The eccentric phase was identified as the time from IC to the time at the lowest vertical position of the COM. The eccentric phase was then subdivided into the loading (i.e., IC to peak vGRF) and absorption phases (i.e., peak vGRF to the lowest vertical position of the COM) using the temporal location of peak vGRF (6,7). The subdivided landing phases were operationally defined by the reaction of the body to the external load. The loading phase represents a short period of time in which the body passively resists the impact force, and the absorption phase indicates a period of time to actively attenuate the external load by the active structures. The joint angles and moments for 15 trials were interpolated to 101 data points and then averaged. The best-fit line of joint angle-moment relationships were calculated using a linear model (5,14,16) and a quadratic model during each phase (Equation 1).

$$Equation\ 1: \hat{y}_i = \beta_0 x_i^2 + \beta_1 x_i + \beta_2$$

Where $\hat{y}_i$ is the estimated joint moment at i^{th} frame for the best-fit curve, x_i is the joint angle at i^{th} frame, and the β_0 is the coefficient of x^2 that represents the width and convexity (or concavity) of the curve (Figure 1). The vertex position of the curve (angle = h, moment = k), can be determined by combinations of coefficients (Equation 2) based on the vertex form of Equation 1 (Figure 1).

$$Equation\ 2.1: \hat{y}_i = \beta_0 (x_i - h)^2 + k$$

$$Equation\ 2.2: h = \frac{\beta_1}{2\beta_0}$$

$$Equation\ 2.3: k = \beta_2 - \beta_0 h^2$$

Since the quadratic does not directly provide a slope of the curve, the function was differentiated to obtain the slope of the tangent lines (Equation 3).

$$Equation\ 3: \hat{y}_i{}' = 2\beta_0 x + \beta_1$$

Using Equation 3, tangent slopes of all data points of the best-fit curve represent the instantaneous joint stiffness. The slopes are then averaged throughout the loading and absorption phases, respectively, to represent the joint stiffness. The obtained stiffness is then compared with the stiffness calculated by the linear model (Figure 1). The root mean squared error (RMSE) and r^2 were calculated using Equation 4 to both relatively and absolutely evaluate the best-fit lines of two models (1,5,14). r^2 indicates how well the best-fit line represents the angle-moment relationship using the scale from 0 to 1 whereas RMSE represents the average distance between the observed data and the best-fit line.

$$Equation\ 4.1: r^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

$$Equation\ 4.2: RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}$$

Where $\bar{y}$ is the average joint moment during each phase.

Statistical Analysis

Multiple 2 by 2 repeated measures ANOVAs were performed using R (18). The independent variables were model (quadratic vs. linear) and phase (loading vs. absorption). The dependent variables were hip, knee, and ankle stiffness, r^2, and RMSE. If a significant interaction effect was found, a *post-hoc* pairwise-comparison was performed with *Bonferroni p*-value adjustment. The *post-hoc* analyses were reported only for the comparisons of interest between phases in the same model and between models in the same phase. This is because it is not meaningful to compare the values across models and phases in this study. Partial ω^2 (ω^2) was reported to indicate the magnitude of difference (small = 0.01, medium = 0.06, large = 0.14) (9). The α was set at .05.

Results

Thirty healthy and active college students participated in this study (Males: Height = 1.82 ± 0.04 m, Mass = 82.4 ± 12.1 kg, Age = 25.8 ± 6.6 years; Females: Height = 1.71 ± 0.09 m, Mass = 64.5 ± 11.2 kg, Age = 25.2 ± 9.2 years). Significant model main effects in r^2 (Hip: $F(1,29) = 72.406$, $p < .001$, $\omega^2 = 0.362$; Knee: $F(1,29) = 28.986$, $p < .001$, $\omega^2 = 0.135$; Ankle: $F(1,29) = 26.761$, $p < .001$, $\omega^2 = 0.126$) and RMSE (Hip: $F(1,29) = 145.043$, $p < .001$, $\omega^2 = 0.269$; Knee: $F(1,29) = 55.958$, $p < .001$, $\omega^2 = 0.325$; Ankle: $F(1,29) =93.255$, $p < .001$, $\omega^2 = 0.421$) in all joints were observed. Significant phase main effects in r^2 of knee stiffness ($F(1,29) = 37.401$, $p < .001$, $\omega^2 = 0.383$) and RMSE of knee ($F(1,29) = 5.364$, $p = .028$, $\omega^2 = 0.080$) and ankle stiffness ($F(1,29) = 9.745$, $p = .004$, $\omega^2 = 0.152$) were found. Also, significant interactions between model and phase were observed in r^2 of all joints (Hip: $F(1,29) = 31.956$, $p < .001$, $\omega^2 = 0.175$; Knee: $F(1,29) = 14.593$, $p < .001$, $\omega^2 = 0.076$; Ankle: $F(1,29) = 11.084$, $p = .002$, $\omega^2 = 0.059$) and RMSE of hip ($F(1,29) = 6.253$, $p = .018$, $\omega^2 = 0.016$) and ankle joint stiffness ($F(1,29) = 11.499$, p 0.002, $\omega^2 = 0.073$) (Table 1).

Significant model main effects in knee ($F(1,29) = 38.550$, $p < .001$, $\omega^2 = 0.030$) and ankle stiffness ($F(1,29) = 18.827$, $p < .001$, $\omega^2 = 0.004$) and significant phase main effects in hip ($F(1,29) = 7.439$, $p = .011$, $\omega^2 = 0.082$) and knee stiffness ($F(1,29) = 112.889$, $p < .001$, $\omega^2 = 0.660$) were observed. Additionally, significant interactions between model and phase were found in stiffness of all joints (Hip: $F(1,29) = 19.574$, $p < .001$, $\omega^2 = 0.015$; Knee: $F(1,29) = 5.223$, $p = .030$, $\omega^2 = 0.003$; Ankle: $F(1,29) = 4.967$, $p = .034$, $\omega^2 = 0.001$) (Table 1).

Discussion

This study was aimed at identifying benefits of a quadratic model to calculate lower extremity joint stiffness in subdivided eccentric phases. The results of the present analyses support our hypothesis that the quadratic model provides better best-fit lines in joint angle-moment relationships. Our major findings were the quadratic model indicated greater r^2 and RMSE for all joint angle-moment relationships. Differences in hip and knee stiffness were identified using the quadratic model when compared to the linear model.

The quadratic model more accurately represented the joint angle-moment relationships for all joints and phases, compared to the linear model. The linear model represented fairly good lines of best-fit for the joint angle-moment curves in the distal joints (knee and ankle) during the loading phase (Table 1 and Figure 2), but the linear model failed to represent the angle-moment relationship during the absorption phase. It hypothesized that the linear model was able to represent the angle-moment relationship only during the loading phase because the muscle-tendon unit of the lower extremities are fully engaged during the absorption phase in response to the external load due to electromechanical delays (3) and laxity of structures. Our data indicated the average time to reach peak VGRF was approximately 50 ms, similar to the electromechanical delays of muscle (3). Thus, the active structure might gradually increase the force production with the increasing joint angles up to the peak vGRF appearance, and then regulate external load for each joint during the absorption phase. However, following the loading phase, the muscle-tendon units actively resist the external load and cause changes in the joint moment throughout the absorption phase.

Additionally, the hip joint had a curvilinear relationship between joint angle and moment even in the loading phase as opposed to the distal joints. This is attributed to the changes in the direction of the resultant GRF vector due to the location of the platform, which mostly affects the moment of the most proximal joint. As seen in Figure 3, the external hip moment kept decreasing after IC until the resultant GRF vector passed the hip joint center, and then increased during the rest of the loading phase. This created a curvilinear relationship between the hip angle and moment, which suggested that the quadratic model could indicate better representation (17). Indeed, the subdivided phases illustrated the benefit of the polynomial equation was greater during the absorption phase across all lower extremity joints.

The quadratic model indicated changes in joint stiffness at the hip and knee between the loading and absorption phase whereas the linear model detected the difference only at knee. The joint stiffness obtained by the quadratic model is likely more sensitive to the joint angle-moment relationship than the linear. For instance, the linear model omits the negative relationship between joint angle and moment as seen in Figure 2, but the quadratic model encompasses the negative slope in the average. The omitted curvilinear or negative relationship caused by the linear model could over- or underestimate the joint stiffness. The linear model likely underestimated the hip joint stiffness during the loading phase (0.022 ± 0.044 $N \cdot m \cdot kg^{-1} \cdot {}^{\circ -1}$) due to the offset induced by the poor best-fit line as compared to the stiffness (0.101 ± 0.052 $N \cdot m \cdot kg^{-1} \cdot {}^{\circ -1}$) calculated by the quadratic model (Table 1 and Figure 2). Also, the average slope (i.e., joint stiffness de~rived from the quadratic model) of the best-fit line relies on the position of the best-fit line vertex. If the vertex of the fitted line with convex shape is positioned at the early or even before the phase, the averaged slope is most likely to be close to zero or even indicate negative joint stiffness (e.g., knee stiffness during the absorption phase; Table 1 and Figure 2).

In summary, details about changes in joint stiffness were obtained by the quadratic model with subdivided eccentric phases, and this model provided better fitted line to obtain joint stiffness as compared to the linear model. The use of the quadratic model for subdivided eccentric phases would provide insight of changes in joint stiffness to absorb and transmit the external loads for the subsequent task.

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Table 2.1. Coefficient of determination (r^2) and stiffness calculated by each model

	Loading		Absorption	
	Linear	Quadratic	Linear	Quadratic
Stiffness ($N \cdot m \cdot kg^{-1} \cdot {}^{\circ -1}$)				
Hip[†,‡]	0.022 (0.044)[‖]	0.101 (0.052)[#]	0.044 (0.050)	0.052 (0.058)
Knee[*,†,‡]	0.052 (0.014)[§,‖]	0.049 (0.015)[#]	0.009 (0.017)[¶]	0.004 (0.017)
Ankle[*,‡]	0.027 (0.023)	0.029 (0.017)	0.046 (0.090)[¶]	0.057 (0.099)
RMSE ($N \cdot m \cdot kg^{-1} \cdot {}^{\circ -1}$)				
Hip[*,‡]	0.114 (0.044)[‖]	0.047 (0.024)	0.124 (0.089)[¶]	0.082 (0.074)
Knee[*,†]	0.071 (0.030)	0.033 (0.012)	0.094 (0.053)	0.058 (0.050)
Ankle[*,†,‡]	0.030 (0.022)[§,‖]	0.015 (0.020)	0.055 (0.024)[¶]	0.024 (0.015)
r^2				
Hip[*,‡]	0.561 (0.310)[§,‖]	0.925 (0.067)	0.782 (0.225)[¶]	0.872 (0.188)
Knee[*,†,‡]	0.966 (0.049)[§,‖]	0.994 (0.004)[#]	0.587 (0.311)[¶]	0.785 (0.254)
Ankle[*,‡]	0.903 (0.235)[‖]	0.934 (0.189)	0.755 (0.263)[¶]	0.922 (0.110)

Note. Mean (SD).
[*] significant model main effect ($p < .05$).
[†] significant phase main effect ($p < .05$).
[‡] significant interaction effect between model and phase ($p < .05$).
[§] significant *post-hoc* analysis between the loading phase of the linear model and the absorption phase of the linear model ($p < .05$).
[‖] significant *post-hoc* analysis between the loading phase of the linear model and the loading phase of the quadratic model ($p < .05$).
[¶] significant *post-hoc* analysis between the absorption phase of the linear model and the absorption phase of the quadratic model ($p < .05$).
[#] significant *post-hoc* analysis between the loading phase of the quadratic model and the absorption phase of the quadratic model ($p < .05$).

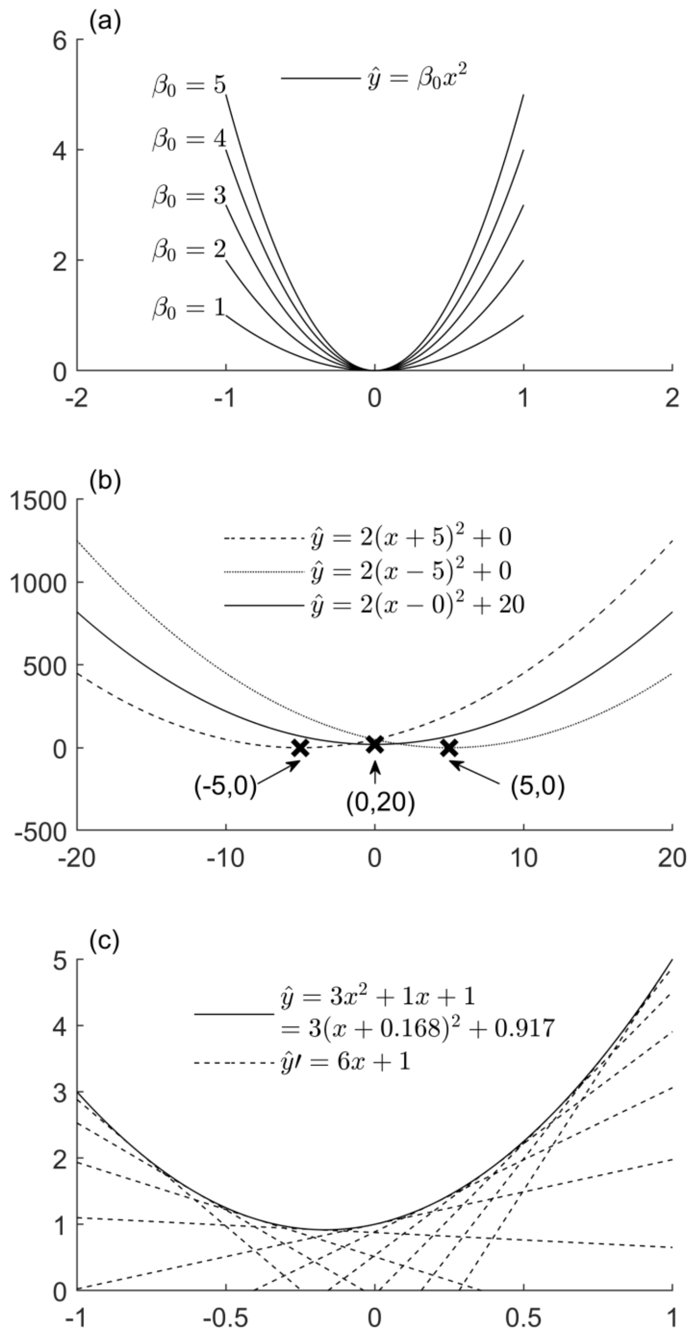

Figure 2.1. Determination of the best-fit line shapes by coefficients of the quadratic model. (a) The coefficient of x^2 determines concavity (or convexity) and width of the best-fit line. (b) The vertex form of the model indicates the location of the vertex of the best-fit line. (c) The differentiated best-fit line indicates the slope of tangent lines for each data point.

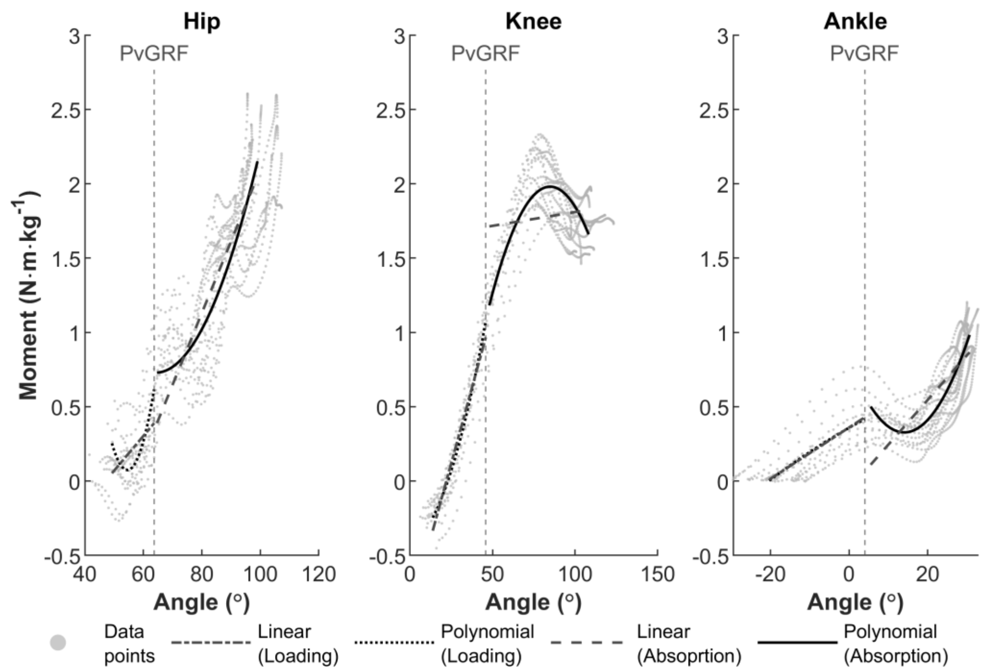

Figure 2.2. Angle-moment curves with the best-fit line estimated by both linear and quadratic models for each loading and absorption phase using 15 trials of drop jump of a single participant. Hip (Linear model during loading phase: $\hat{y} = 0.023x - 1.10$, r^2= 0.442; Polynomial model during loading phase: $\hat{y} = 0.007x^2 - 0.706x + 19.311$, r^2= 0.967; Linear model during absorption phase: $\hat{y} = 0.048x - 2.731$, r^2= 0.924; Polynomial model during absorption phase: $\hat{y} = 0.001x^2 - 0.151x + 5.572$, r^2= 0.972); Knee (Linear model during loading phase: $\hat{y} = 0.041x - 0.892$, r^2= 0.981; Polynomial model during loading phase: $\hat{y} = 0.001x^2 + 0.005x - 0.425$, r^2= 0.998; Linear model during absorption phase: $\hat{y} = 0.002x + 1.624$, r^2= 0.032; Polynomial model during absorption phase: $\hat{y} = -0.001x^2 + 0.1x - 2.263$, r^2= 0.899); Ankle (Linear model during loading phase: $\hat{y} = 0.017x + 0.360$, r^2= 0.996; Polynomial model during loading phase: $\hat{y} = -0.0001x^2 + 0.015x + 0.35$, r^2= 0.998; Linear model during absorption phase: $\hat{y} = 0.030x - 0.055$, r^2= 0.771; Polynomial model during absorption phase: $\hat{y} = 0.002x^2 - 0.067x + 0.795$, r^2= 0.988).

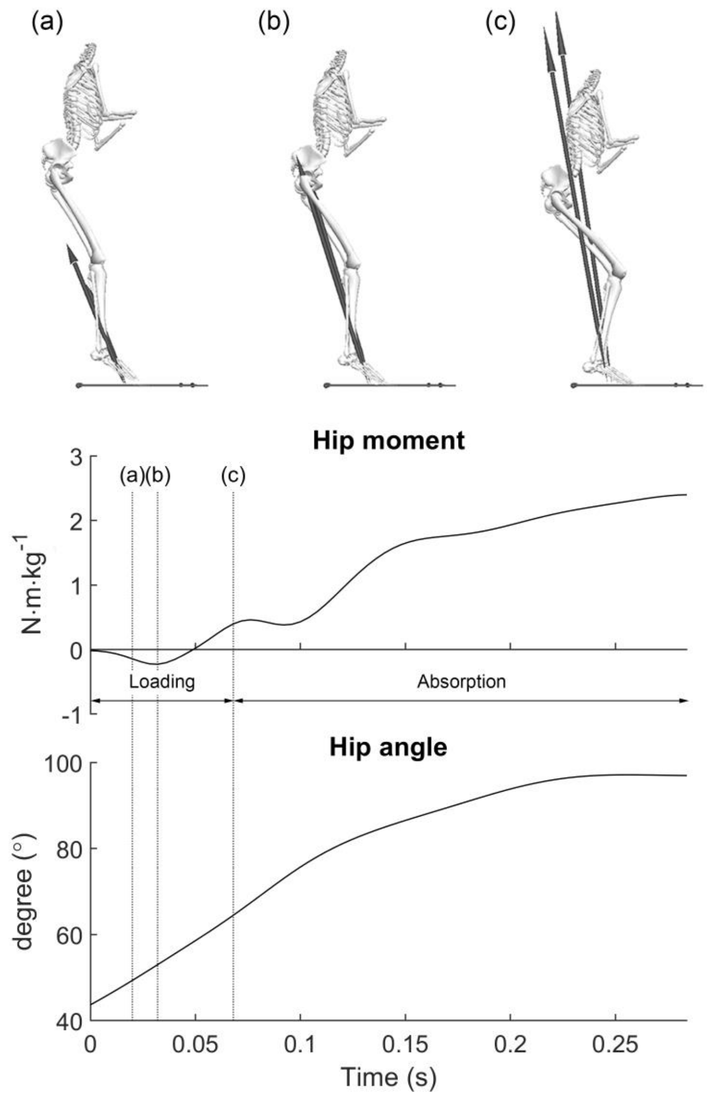

Figure 2.3. The changes in the hip joint angle and moment by the direction of the resultant GRF vector during the eccentric phase of the drop jump. (a) 20 ms after IC, (b) minimum hip joint moment, and (c) the end of the loading phase (i.e., at peak vertical ground reaction force).

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Chapter 3: Differences in Lower Extremity Joint Stiffness during Drop Jump between Healthy Males and Females

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.

Introduction

Sport participation often necessitates repetitive propulsive vertical jumps and landings, requiring lower extremity structures, such as muscles and tendons, to interact mechanically and regulate the body's response to external forces during movement. A simple model depicting the interaction of the collective lower extremity structures during jumping activities is a linear spring in the spring-mass model (Blickhan, 1989). The model illustrates the system's interaction with an external load during sports-related movements 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 structures and 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 an individual joints' angle-moment relationship (Farley & Morgenroth, 1999; Ford et al., 2010; Horita et al., 2002; Schmitz & Shultz, 2010; Stefanyshyn & Nigg, 1998).

Joint stiffness is often used to evaluate potential indicators of performance in sport-related movements (Arampatzis et al., 2001; Farley & Morgenroth, 1999; Stefanyshyn & 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 during the eccentric phase (Hamill et al., 2015). Modulation to increase joint stiffness can occur through increased torque about the joint or by a reduction in angular position changes in response to the load. These modulations may induce greater stress, and thus strain, on the muscle-tendon unit during the active stretch. 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 strain energy is released during the propulsive phase, potentiating the demand for force production (Komi, 2003). For instance, increased ankle (Stefanyshyn & Nigg, 1998) and knee (Kuitunen et al., 2002) stiffness have been found with increased running velocity.

Potential differences in joint stiffnesses have also been reported between sexes (Ford et al., 2010; Schmitz & Shultz, 2010). Males have demonstrated increased hip (Ford et al., 2010; Schmitz & Shultz, 2010), knee, and ankle stiffness (Ford et al., 2010) during a drop jump task compared to females. The increased joint stiffness in males was attributed to small changes in joint angle combined with increased external joint moment (Ford et al., 2010; Schmitz & Shultz, 2010). However, sex differences in knee stiffness were not present when the joint moment was normalized by body mass (Ford et al., 2010). The influence of sex in relation to joint stiffness has been investigated through the injury risk lens, but not through a jump performance lens (Ford et al., 2010; Schmitz & Shultz, 2010). Furthermore, it is unknown whether lower extremity joint stiffness variables during the eccentric phase are important contributors to the vertical jump height .

Sex differences have also been identified in kinetic variables along with an increase in countermovement jump height in males (Ebben et al., 2007; Laffaye et al., 2014; McMahon et al., 2017; Rice et al., 2016; Riggs & 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 & Sheppard, 2009), and peak power during the concentric phase (McMahon et al., 2017; Riggs & Sheppard, 2009; Rubio-Arias et al., 2017) to achieve a higher countermovement jump height. Thus, males are likely to achieve increased jump performance by utilization of a greater force production combined with a reduced duration than females. Thus, increased joint stiffness may enhance jump performance in males by reducing contact time and increasing peak force production. 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, jump height, and net jump impulse as compared to females. We also hypothesized that the female regression model would include different explanatory variables than males as predictors of jump height.

Methods

The study was approved by the University Institutional Review Board and all participants signed a university approved informed consent from prior to participation. Thirty healthy and active college students participated in the study. Participants were regularly engaged in physical activities (at least 30 minutes with moderate-intensity for 5 days per week or at least 20 minutes with vigorous-intensity for 3 days per week), self-reported good health (i.e., not suffering from a current injury or recent history of surgery on their lower extremity, pelvis, and lower back), and identified a dominant leg (i.e., the preferred leg to kick a soccer ball; Weinhandl et al., 2015).

Participants then performed a 5-minute self-selected warm-up (treadmill, stationary bike, or dynamic warm-up). Participants wore tight spandex style shorts and were instrumented with a full-body cluster-based marker set using passive reflective markers post warm-up. The clusters were attached to thigh and shank segments with elastic wraps (SuperWrap, fabrifoam®, Applied Technology International, Ltd., Exton, PA, USA), and other individual reflective markers used for dynamic trials were attached to feet, upper-limbs, pelvis, and trunk and secured with athletic tape.

Participants performed two practice trials at each box height of 30 (Padua Michelle C Boling & DiStefano James A Onate Anthony I Beutler, 2011) and 60 cm (Arampatzis et al., 2001; Walsh et al., 2004); participants then completed 15 trials of a drop vertical jump at the two heights. The box was located at a horizontal distance equal to half of the participant’s height from the center of two embedded force platforms for each box condition. Participants were instructed to stand on the edge of the box, drop off without jumping upward, and to land with one foot completely on each force platform (Padua et al., 2009). Participants were instructed to perform a maximal vertical jump immediately following ground contact with the force platforms. A minimum of a 30-second rest (longer if needed) between trials was provided to protect against muscular fatigue. 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 box height conditions was counterbalanced across participants.

The drop vertical jump trials were captured at 250 Hz sampling rate using a 3-D motion capture system (NEXUS 2.6, Vicon Motion System Ltd., Oxford, UK) with 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 and used to collect GRF data at 1000 Hz sampling rate. To filter marker trajectory and GRF data, the C3D files of each trial were imported to MATLAB (MATLAB 2019b, MathWorks, Natick, MA, USA). A power spectral density analysis was performed to select the optimal cut-off frequency on marker trajectories using lower extremity markers. The optimal cut-off frequency was selected as the minimum frequency that maintained 99% of the original signal for each participant's marker trajectories and GRF data. The determined optimal cut-off frequency ranged from 6 – 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 2^{nd} order Butterworth filter (Kristianslund et al., 2012). The filtered data were imported to Visual 3D software (Visual 3D v6 Professional, C-Motion, Inc., Germantown, MA, USA) to calculate lower extremity joint angles and external moments. The direction of rotation of lower extremity 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.

Raw data were extracted and imported into MATLAB software to calculate the variables of interest. To determine the ground contact period vGRF threshold was set to 20 N (Krosshaug et al., 2016). Ground contact period was from the initial contact (IC: vGRF > 20N) to toe-off (TO: vGRF < 20N) after dropping off from the box (Ford et al., 2003). The ground contact period was subdivided into three subphases: loading, absorption, and propulsion phases. The loading phase was defined as IC to the time of the first peak vGRF (PvGRF); the absorption phase was from PvGRF to the lowest vertical position of the COM (COM_{min}) (Harry et al., 2018); the propulsion phase was from COM_{min} to TO.

The relationships between joint moment and angle change in this study were non-linear during particular phases. Therefore, to best represent joint stiffness, a line of best fit was calculated using a polynomial regression equation during the loading and absorption phases. The 2nd order polynomial regression model was repressed by Equation 1.

$$Equation\ 1: \quad y = \beta_0 x_i^2 + \beta_1 x_i + \beta_2$$

Where $\hat{y}$ is the estimated joint moment, $x_i$is joint angle, and the β_0 is the coefficient of x^2 that represents the width and convexity (or concavity) of the fitted curve. The vertex position of the fitted curve can be determined by combinations of coefficients (Equation 2.2) based on the vertex form of Equation 1.

$$Equation\ 2.1: \quad y = \ \beta_0 (x_i - h)^2 + k$$

$$Equation\ 2.2: \quad h = \frac{\beta_1}{2\beta_0}$$

$$Equation\ 2.3: \quad k = \beta_2 - \beta_0 h^2$$

Because the fitted line calculated by the polynomial regression model does not directly provide the slope, the model was differentiated to obtain the slopes at each data point (Equation 3).

$$Equation\ 3: \quad y' = 2\beta_0 x_i + \beta_1$$

The slopes representing the loading and absorption phases were then averaged to provide an estimate of joint stiffness. The coefficients of determination (r^2) were calculated for each polynomial regression model to identify how well the equation represents the data (Arampatzis et al., 2001; Ford et al., 2010; Padua et al., 2005).

Other dependent variables of interest 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 vGRF exceeding the participant's body weight during the propulsion phase (Figure 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 from vertical position at TO to the highest vertical position of the COM.

Statistical analyses were performed using R software (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 the desired number of trials for each box height between males and females. Multiple mixed 2-way ANOVAs were performed with two independent variables: box height (within factor) and sex (between factor). All dependent variables were joint stiffnesses, associated r^2 during the loading and absorption phases, and all other spatiotemporal and kinetic variables. To indicate the magnitude of differences, the effect size, partial omega squared (partial 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 analysis was performed with Tukey's HSD for pairwise comparisons. Multiple regressions for each male and female 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 know relationship of the two variables. Alpha for all statistical analyses was set at .05.

Results

Significant differences were observed for height (t = 4.330, p < .001) and body mass (t = 4.204, p < .001) between males (ht = 1.82 ± 0.04 m, BM= 82.4 ± 12.1 kg) and 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.

There was no significant interaction effect and sex main effect in the joint stiffness and r^2 during the loading phase. Significant box main effects were observed in hip (F(1,28) = 28.077, p < .001, partial ω^2 = 0.203) and knee (F(1,28) = 31.313, p < .001, partial ω^2 = 0.278) stiffness during the loading phase (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, partial ω^2 = 0.179; Knee: F(1,28) = 7.449, p = .011, partial ω^2 = 0.075; Ankle: F(1,28) = 4.609, p = .041, partial ω^2 = 0.013).

During the absorption phase, significant interaction effects were observed in the hip stiffness (F(1,28) = 6.364, p = .018, ω^2 = 0.015), r^2 (F(1,28) = 6.364, p = .018, ω^2 = 0.015), and r^2 of the hip (F(1,28) = 5.035, p = .033, ω^2 = 0.021) and the knee (F(1,28) = 6.724, p = .015, ω^2 = 0.019) during the absorption phase (Table 2 and Figure 2). Significant sex main effects were found in hip stiffness (F(1,28) = 8.461, p = .007, ω^2 = 0.199), r^2 of hip (F(1,28) = 10.930, p = .003, ω^2 = 0.249) and knee (F(1,28) = 14.630, p < .001, ω^2 = 0.312). Knee (F(1,28) = 8.259, p = .008, partial ω^2 = 0.028) and ankle (F(1,28) = 22.984, p < .001, partial ω^2 = 0.048) stiffnesses were significantly reduced regardless of sex in the 60 cm box compared to the 30 cm box. The 60 cm box significantly reduced r^2 of the hip (F(1,28) = 41.607, p < .001, partial ω^2 = 0.180) and knee (F(1,28) = 76.682, p < .001, partial ω^2 = 0.206), but there was an increased r^2 for the ankle (F(1,28) = 36.700, p < .001, partial ω^2 = 0.094) as compared to the 30 cm box.

A significant interaction was observed in GRF_1 ($F(1,28) = 8.101$, $p = .008$, partial $\omega^2 = 0.031$) (Table 3 and Figure 2). In addition, the 60 cm box significantly increased GRF_1 ($F(1,28) = 222.341$, $p < .001$, partial $\omega^2 = 0.495$) as compared to the 30 cm box regardless of sex. Males possessed greater GRF_2 ($F(1,28) = 6.034$, $p = .021$, partial $\omega^2 = 0.144$), net jump impulse ($F(1,28) = 32.490$, $p < .001$, partial $\omega^2 = 0.512$), and jump height ($F(1,28) = 36.320$, $p < .001$, partial $\omega^2 = 0.541$) compared to females.

The multiple regression model predicting jump height was significant for females ($p < .001$), but not significant for males ($p = 0.609$) (Table 4). The female model included hip ($p = .006$) and knee ($p = .029$) stiffness during the loading phase as significant predictor variables (Table 4).

Discussion

Our study had two purposes: 1) to investigate potential sex differences in lower extremity joint stiffness during the eccentric phase of 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. Interestingly, males had greater hip stiffness at the lower box height than females at the higher box. The major findings of this study were that joint stiffness was only a predictor of drop jump height for females. The only stiffness variables 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 stiffness during the loading phase of the eccentric movement was a surprise. However, this may be attributed to the lack of differences in the external joint moments normalized by body mass and the short duration of the loading phase. Figure 3 demonstrates similarities of sex group mean joint angle and moments as a percentage of the cycle. This indicates a similar approach to the initial contact and loading response across sex groups. Furthermore, the neuromuscular inability to modulate muscle force via active contraction may add to the lack of sex differences regardless of size and strength differences. Electromechanical delays of approximately 50 ms have been reported for maximal force production in response to muscle contraction (Cavanagh & Komi, 1979). This delay coupled with the potential of the muscles and tendons containing some slack (i.e., lack of tension) at the beginning of the loading phase, may prevent the potential lower extremity structural and training differences between sexes to be fully activated during the loading phase. The electromechanical delay reported by Cavanagh & Komi (1979) for the maximal muscle contractions, is similar to the mean duration of the loading phase (t_1) in the present study for both sex (Table 3).

Sex differences in stiffness were found to occur at the hip, with males possessing a stiffer hip than females. Interestingly, males even possessed a stiffer hip during the lower box height than the females did during the higher box (Figure 2: a). As seen in Figure 3, males exhibited greater hip moment throughout the absorption phase. This increased hip external flexion moment in males may reflect efficient muscle force transmission during the complex movement tasks like a drop jump (Bojsen-Møller et al., 2005; Schmitz & 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 lower extremity joint stiffnesses to achieve maximal jump height following a box jump are seen in comparing regression models. The female predictive 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 & Nigg, 1998). These differences can be attributed to the task differences in between running and box jumps. Both running and drop jumping required that the individual structures must overcome the braking forces in posterior and vertical directions during the eccentric phase by modulating lower extremity 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 joint (Figure 4) to stop the vertical motion of the systems center of mass prior to executing the subsequent jumping (DeVita & Skelly, 1992). The positive relationship between hip and knee stiffness and drop jump height for females indicate that the increased stiffness is beneficial to jump height. Females have been found to exhibit greater negative work in knee joint than males (Schmitz & Shultz, 2010). This supports a reliance on the knee for females to increase jump height as demonstrated by the greater 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 in this study had greater hip stiffness during the absorption phase than females, their joint stiffness did not account for drop 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 stretch-shortening cycle as much as females to achieve jump performance.

In addition to the limited sex differences found in this study, box height differences were found across all participants. The increase in box height caused a reduction in hip stiffness during the loading phase, but increased knee stiffness regardless of sex. 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 (Figure 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. 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 (Figure 4). However, it is possible that the increased compliance is attempting to optimize the stiffness of those joints to appropriately engage the stretch-shortening cycle to effectively utilize the external load, which may also be a strategy to reduce the impact of the landing.

While we recruited individuals who were regularly engaging in physical activity, a potential study limitation is that we did not control for 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 & Marini, 1987) and plyometric training type II muscle fibers (Almeida-Silveira et al., 1994; Goubel & Marini, 1987), which also affect the stiffness of the muscle-tendon unit (Almeida-Silveira et al., 1994; Fouré et al., 2010; Goubel & Marini, 1987). Thus, the sex difference in joint stiffness, impulse, and jump performance found in this study may also encompass the effect of different exercises on joint stiffness, impulse, and jump performance due to a greater proportion of participation in aerobic endurance exercises in females than males.

In summary, the present study evaluated sex differences in lower extremity joint stiffness using subdivided phases of drop jumps and jump performance. Males tended to perform drop jumps by stiffening the joints during the loading phase to effectively utilize the impact force. Conversely, females tended to absorb the impact force with increased compliance. Using these different joint stiffness strategies, males jumped higher than females. Interestingly, lower extremity joint stiffnesses were only predictors for females in the drop jump task.

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Table 3.1. 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								
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 sex. † indicates a significant main effect for box height.

Table 3.2. 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								
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.

Table 3.3. 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.

Table 3.4. Multiple regression models for each male and female

	Male			Female		
	β	*t*	*p*	*β*	*t*	*p*
Intercept	0.309	7.36	< .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			< .001*	
adjusted r^2		-0.053			0.579	

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

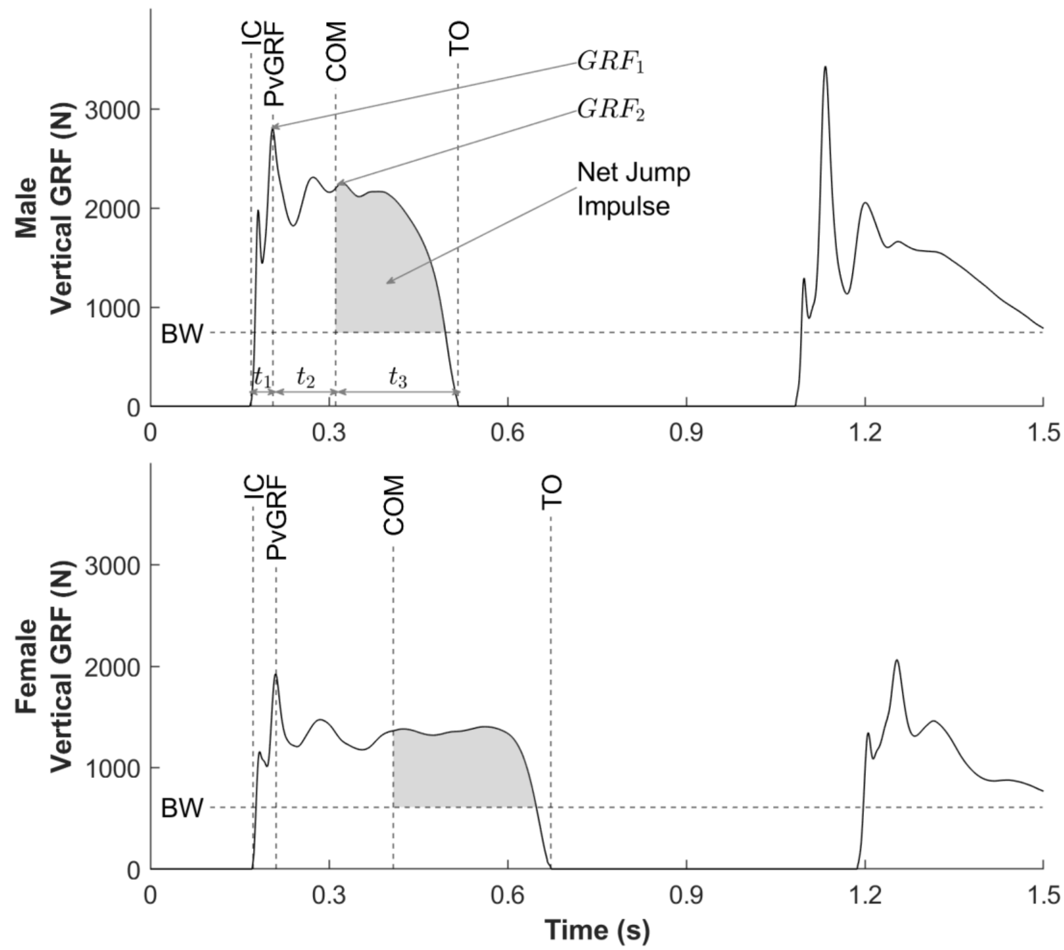

Figure 3.1**.** Example of the vGRF-time curve for each male and female. BW: Body weight, IC: Initial contact, PvGRF: Peak vertical ground reaction force, COM: Lowest COM position, TO: Toe-off, t_1: Time window of the loading phase, t_2: Time window of the absorption phase, t_3: Time window of the propulsive phase, GRF_1: PvGRF, GRF_2: vGRF at the center of mass located the lowest vertical position.

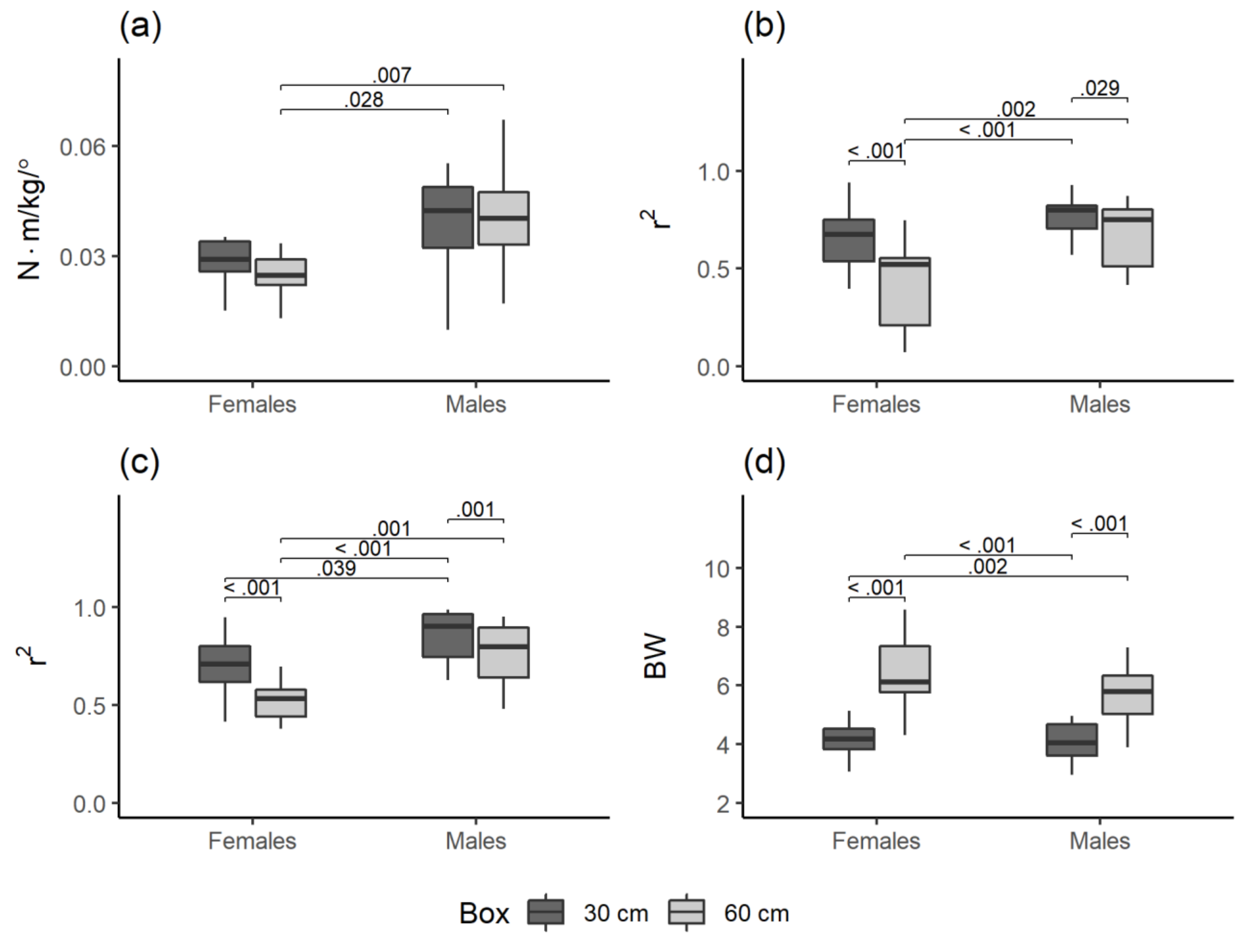

Figure 3.2. Box plots of the variables indicating significant interaction effects between box and sex. (a) Hip stiffness during the absorption phase, (b) r^2 of the hip joint during the absorption phase, (c) r^2 of the knee joint during the absorption phase, and (d) peak vertical ground reaction force (GRF_1). Numbers on brackets indicate significant *p*-values of each comparison in post-hoc analyses.

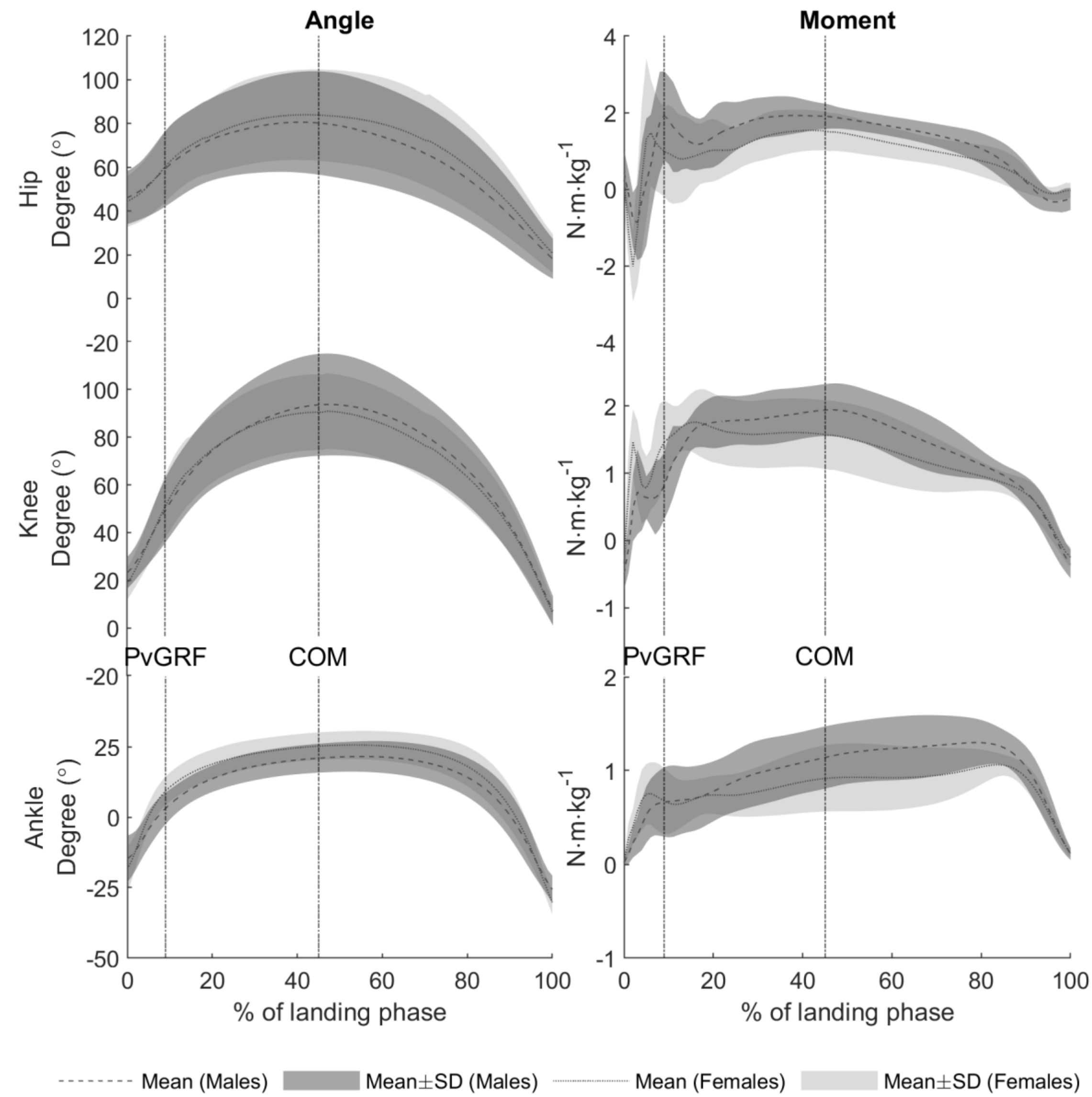

Figure 3.3. Sex group mean angles and moments of hip, knee, and ankle joints during the ground contact period . PvGRF: Peak vertical ground reaction force; COM: The center of mass located at the lowest position.

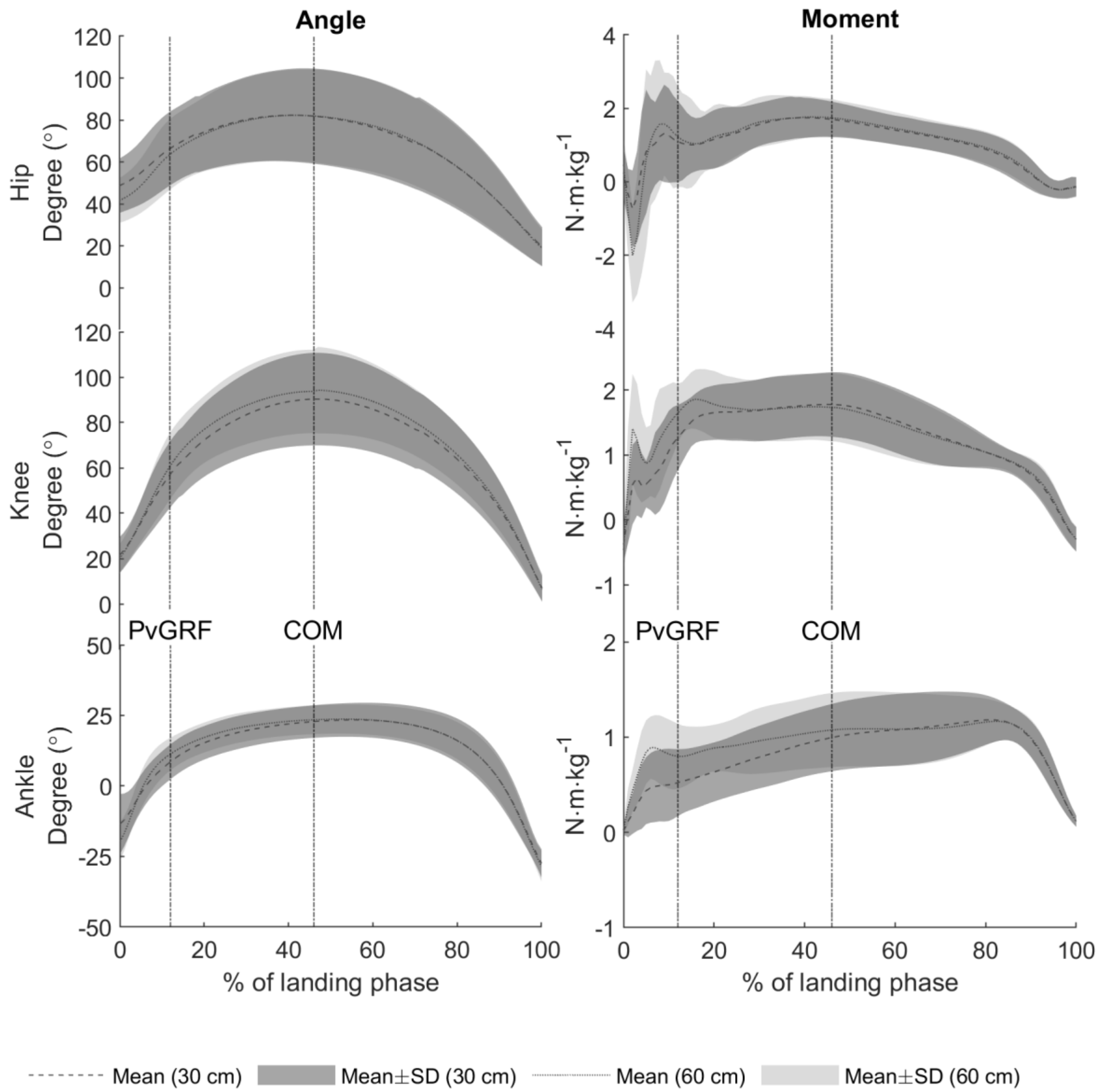

Figure 3.4. Box height group mean angles and moments of hip, knee, and ankle joints during the ground contact period. PvGRF: Peak vertical ground reaction force; COM: The center of mass located at the lowest position.

Chapter 4: Differences in Jump Performance, Joint Stiffness, and Isokinetic Strength between Female athletes and Ballet-trained Dancers

Abstract

The primary purpose of this study was to examine differences in jump performance and joint stiffness between female college athletes. A secondary purpose was to identify the relationship between drop jump performance and both joint stiffness and isokinetic strength. Twenty-seven female collegiate athletes were recruited and allocated to three groups: Basketball/volleyball (BV), soccer (SOC), and dance (DAN). Eccentric/concentric isokinetic strength of lower extremity extensors were measured using an isokinetic dynamometer. Lower extremity joint stiffnesses during the loading and absorption phases of drop jumps were calculated by a 2nd order polynomial regression model. BV had significantly greater jump height (p = .004) and jump impulse (p = .004) with reduced hip joint stiffness during the loading phase (p = .04) than DAN. No differences in isokinetic strength were observed. The stepwise regression analyses showed that each female athletic group had different joint stiffness and isokinetic peak torque predictors to maximize drop jump height. This study identified that each athletic group had different joint dominance for drop jump performance, which is likely attributed to differences in sport and training demands.

Introduction

Vertical jumps are typically performed in a combined form with other preceding movements such as running or landing rather than independently performed in most sports. Combining the preceding movement utilizes the mechanical advantages of human body to improve the jump performance as compared to the vertical jump without the preceding movement (Bobbert et al., 1996). This mechanical advantage is attributed to the stretch shortening cycle facilitating uses of the elastic energy stored in soft tissues during the preceding movement (Komi, 1984, 2003).

The ability to store and utilize the elastic energy could be affected by individuals' training histories or the demands of their sports (Kubo et al., 2007). Specifically, amateur basketball players who repeatedly perform vertical jumps had stiffer Achilles tendon and gastrocnemius medialis as compared to non-athletes (Chang et al., 2020). The stiffer tendon and muscle are most likely adaptations to the repeated loading of training (Albracht & Arampatzis, 2013; Chang et al., 2020;

Dirrichs et al., 2019) and causes increased passive ankle torque (Kawakami et al., 2008). The increased passive ankle torque could improve performance by the increased energy storage and return (Albracht & Arampatzis, 2013).

Conversely, dancers possessed more compliant Achilles tendons than healthy controls (Moltubakk et al., 2018) even though they are also exposed to repeated vertical loadings in their training and performance routines (Ward et al., 2019). Dancers were also more compliant in the leg, knee, and ankle compared to team sport athletes, which has been attributed to the aesthetic demands of the landing in dance for performance (Liederbach et al., 2008; Orishimo et al., 2009; Ward et al., 2019). Specifically, the dance aesthetic requires controlled landings by sequentially flexing the lower limbs in order of distal to proximal joints in dancers (Orishimo et al., 2009). When considering the landing of dancers based on the concept of the stretch-shortening cycle, the smooth landing demands of dancing may not fully require the storage and return of elastic energy for the jump performance. No difference in jump performance between dancers and healthy controls was observed despite the greater knee extensor strength in dancers (Harley et al., 2002). Stiffness differences between dancers and basketball players illustrate potential differences in mechanical properties and their potential relationship jump training and plyometric loads. However, it is unclear if athletes have different joint stiffness characteristics in accordance with their sports demands and if joint stiffness from a previous box drop directly influences jump performance.

In addition to passive structures, the contractile components of skeletal muscle directly contribute to joint stiffness and jump performance producing force and regulating segmental movement. Concentric isokinetic peak torques of hip and knee joint at high velocity (i.e., 180 °/s) have been shown to have a moderate relationship with both squat and countermovement jump performances (Tsiokanos et al., 2002). Furthermore, knee concentric extension peak torque was identified as the most significant predictor of jump height of drop jump task, with a lack of relationship between eccentric peak torque and jump performance (DeStaso et al., 1997). Even though the increased eccentric strength is likely associated with jump performance in that it may increase joint stiffness and then facilitate the stretch shortening cycle, there is still the paucity of evidence of the relationship between jump performance and eccentric strength.

Therefore, the purposes of the present study were two-folded. The primary purpose was to examine differences in jump performance and lower extremity joint stiffness between female college athletes possibly influenced by sports specific demands. We hypothesized that female athletes who required frequent jumps in their sports (i.e., volleyball and basketball players) would have increased joint stiffness and drop jump performance as compared to dancers focusing more on landings. The secondary purpose was to identify the potential relationship between drop jump performance and both joint stiffness and isokinetic strength. It was hypothesized that drop jump performance would have a positive relationship with joint stiffness and isokinetic strength.

Methods

Participants

A total of 27 collegiate female athletes (basketball = 5, volleyball = 4, soccer = 8, ballet-trained dancers = 10) were recruited from a Division 1 University. Female basketball (n =5) and volleyball players (n =4) were allocated to the same group because both sports presented similar jumping workloads. Thus, three groups were created – dancers (DAN), soccer (SOC), and basketball/volleyball (BV) – for this study. All athletes were actively participating in their identified sport as a collegiate student at the time of participation. Athletes were excluded from participation if they had lower extremity or low back injuries or any pain during sports-related movements.

Procedure

All participants signed an informed consent approved by the Institutional Review Board at the university upon arrival to the laboratory and then answered a short questionnaire to identify histories of resistance and plyometric exercises. Body mass and height were measured prior to a 5-minute self-selected warm-up. Preferred limb was determined for each group of athletes for analysis (BV: the ipsilateral leg of the arm used to spike a volleyball, or the contralateral leg of the arm used for a layup; DAN: the leg used for stability during turning; SOC: the dynamic leg used to kick a ball). Isometric strength tests were then performed in order of knee, hip, and ankle joints for both limbs. Participants were given a practice trial consisting of 3 submaximal consecutive repetitions of concentric and eccentric contractions for each test to be familiar with the testing protocols. At least 30 seconds of rest was provided following the practice and then the 3 maximal repetitions of each test were collected.

3D motion capture during drop jump tasks was collected using a customized full body marker set was used (Figure 1). Individual reflective markers were attached to anatomical bony landmarks of foot, pelvis, torso, upper arms, and forearms and then secured with athletic tapes (Leukotape® P, BSN medical GmbH, Hamburg, Germany; Cover-Roll® stretch, BSN medical GmbH, Hamburg, Germany). Four rigid clusters were placed on the lateral aspect of thigh and shank segments and secured with elastic wraps (SuperWrap, fabrifoam®, Applied Technology International, Ltd., Exton, PA, USA).

Participants performed up to 5 drop jump trials from each 30 cm and 60 cm boxes, and only successful trials (i.e., feet landed within the force platform borders) were analyzed. The order of box heights was counterbalanced to avoid an order effect on dependent variables. Each box was placed a distance half of the participant's height from the center of two embedded force platforms (Padua et al., 2009). They were then instructed to stand on the box with their toes as close to the edge as possible, drop off from the box by leaning forward, and jump up as high as possible upon landing on the force platforms. Instructions were not given as to what to do with arms during the task, allowing participants the freedom to use their arms as they deemed fit to generate their maximum jump height (Feltner et al., 2004). Participants were allotted to two practice trials per box height and as much rest between trials as they needed.

Isokinetic strength test protocols

An isokinetic dynamometer (HUMAC NORM, Computer Sports Medicine Inc., Stoughton, MA, USA) was used to measure isokinetic strength for knee extension, hip extension, and ankle plantarflexion at 100 Hz sampling rate. The protocols consisted of 3 repetitions of maximal concentric/eccentric contractions. The angular velocities of each joint were set as the closed velocities to the average joint angular velocities during the eccentric phase of drop jump determined by our previous research. The determined tested average angular velocities were set at 100 $°/s$, 180 $°/s$, and 100 $°/s$ for hip, knee, and ankle joints respectively.

All isokinetic measurements followed HUMAC NORM protocols established by CSMi. For knee extension, participants were secured by seatbelt and Velcro straps to isolate knee sagittal plane movement in the seated position. Participants were asked to cross their arms in front of their chest during the test to prevent the influence of the upper body and other muscles on the targeted muscle torque production (Figure 2 a). Hip extension was performed in the supine position with crossing arms and secured pelvis by a Velcro strap. Participants were instructed to naturally flex and extend their knee during the hip isokinetic strength test (Figure 2 b). Ankle plantarflexion was measured in the prone position (Figure 2 c).

3D motion captures and data processing

Drop jump tasks were captured by a 3D motion capture system (NEXUS 2.9, Vicon Motion System Ltd., Oxford, UK) with 8 infrared cameras (VANTAGE 5, Vicon Motion System Ltd., Oxford, UK) and 2 synchronized force platforms (OR6-6, AMTI, Watertown, MA, USA). The sampling rate of the 3D motion capture system and force platforms were 250 Hz and 2000 Hz, respectively.

Each participant's raw data were imported to a customized script (MATLAB 2020a, MathWorks, Natick, MA, USA) to perform Power Spectral Density in order to determine an optimal cut-off frequency for the lowpass filter at which 99% of the signals can be obtained. The Power Spectral Density was performed for marker trajectories and the ground reaction force (GRF) data, separately. The determined cut-off frequencies for marker trajectories filters ranged from 6 to 26 Hz (14.4 ± 5.11 Hz) and from 41 to 97 Hz (65.3 ± 13.2 Hz) for force platform data. Using these determined cut-off frequencies, each participant's data were lowpass filtered with 2nd order Butterworth filter.

Visual3D software (Visual3D v6 Professional, C-Motion, Inc., Germantown, MA, USA) was used to build a model based on the filtered data. Since the CODA model was used to create the pelvis segment, the hip joint centers were estimated based on markers on the anterior superior iliac crest (Bell et al., 1989, 1990). The knee and ankle joint centers were estimated based on medial and lateral markers on knee joint lines and malleoli, respectively. The calculated lower extremity joint angle, moment, center of mass of the body (COM), and filtered GRF data were exported as Mat file format for the further data reduction.

The initial contact to the ground (IC) and toe-off (TO) were identified using a threshold of 20 N of the vertical GRF. The eccentric phase of the drop jump was defined as the period from IC to when the COM reached the lowest vertical position. The remaining contact period was defined as the propulsive phase. Previous work in our lab (unpublished) identified calculation difficulties representing the entire eccentric phase in specific joints, leading to a subdivision of this phase. The eccentric phase was subdivided into the loading and absorption phases based on the peak vertical GRF to calculate joint stiffness. The subdivided landing phases were operationally defined by the reaction of the body to the external load. The loading phase represents a short period of time in which the body passively resists the impact force, and the absorption phase indicates a period of time to actively attenuate the external load by the active structures.

Separate 2nd order polynomial regression model was used to calculate the lines of best-fit for the joint angle-moment curves for the loading and absorption phases. Since the line of best-fit obtained by the 2nd polynomial regression model does not directly identify the slope (i.e., stiffness), the regression equation was differentiated to obtain slopes of the tangent line of each data point (i.e., percent cycle). The slopes of the tangent lines were then averaged to indicate the joint stiffness for each loading and absorption phase. Mean vertical stiffness was calculated for each subphase using vertical GRF-COM curve.

Jump impulse was calculated using the area under the vertical GRF-time curve during the propulsive phase minus the area under the bodyweight level (Figure 3) and then normalized by body mass (m/s). Jump height was determined by calculating the difference between the vertical position of the COM at TO and the highest vertical position of the COM after TO.

Statistical analyses

R software (Team, 2020) was used to perform statistical analyses. Multiple one-way ANOVAs were performed to compare demographic information and peak torque of isokinetic strength tests between female athletic groups. Multiple two-way mixed model ANOVAs were performed with two independent variables, group (BV vs. DAN vs. SOC) and box (30 cm vs. 60 cm). Effect size, partial ω^2 (ω^2) was reported to indicate the magnitude of difference (small = 0.01, medium = 0.06, large = 0.14; Kotrlik et al., 2011). If a significant group main effect was found, a pairwise comparison was performed with Tukey adjusted *p*-value. Stepwise regressions for each group and overall female athletes were performed to select independent variables for the final model identifying what variables are predictors of jump height. The initial model included jump height as a dependent variable, with all joint stiffnesses and peak torques of eccentric/concentric isokinetic strength tests as independent (i.e., predictor) variables. Alpha for all statistical analyses was set at .05.

Results

The average numbers of drop jump trials were not significantly different between groups ($F(2,24) = 0.382$, $p = .687$) and between boxes ($F(2,24) = 0.000$, $p = 1.000$). The number of trials were 4.14 ± 0.85 for 30 cm box (ranged from 2 to 5) and 4.14 ± 0.93 for 60 cm box (ranged from 2 to 5), respectively. There was no significant difference in age between groups, but significant group main effects were observed in height, body mass, history of resistance exercise, and history of plyometric exercise (Table 1). The *post-hoc* analyses revealed that BV was significantly taller than both DAN ($t(24) = -5.563$, $p < .001$) and SOC ($t(24) = -4.218$, $p < .001$), with greater body mass than DAN ($t(24) = -3.972$, $p = .001$), and had more resistance and plyometric training history than both DAN (Resistance exercise: $t(24) = -5.987$, $p < .001$; Plyometric exercise: $t(24) = -4.225$, $p < .001$) and SOC (Resistance exercise: $t(24) = -3.529$, $p = .004$; Plyometric exercise: $t(24) = -3.800$, $p = .003$).

Significant group main effects were found for both jump height ($F(2,24) = 6.455$, $p = 0.006$, $\omega^2 = 0.288$) and jump impulse ($F(2,24) = 6.563$, $p = 0.005$, $\omega^2 = 0.292$) (Table 2). *Post-hoc* analyses revealed that BV had a greater jump height ($t(24) = 3.590$, $p = .004$) and jump impulse ($t(24) = 3.612$, *p* = .004) compared to DAN. While the jump impulse in 60 cm condition was significantly greater than the 30 cm condition ($F(2,24) = 10.283$, $p = .0040$), the effect size was negligible ($\omega^2 = 0.006$).

No significant interaction was observed. A significant group main effect was observed in hip stiffness during the loading phase with a large effect size ($F(2,24) = 3.816$, $p = 0.036$, $\omega^2 = 0.173$) (Table 3). In the *post-hoc* analysis, DAN had a stiffer hip than BV ($t(24) = -2.606$, $p = .04$) during the loading phase. A box main effect was also found in vertical stiffness during the loading phase with a small effect size ($F(2,24) = 7.722$, $p = .010$, $\omega^2 = 0.038$). All peak torques of the isokinetic strength tests were not significantly different between female athletes (Table 4).

Stepwise regression equations for each group and female athletes overall as a group were all significant (Table 5 and Figure 4). The regression equation for all female athletes as a group accounted for only 19.6% of variance in drop jump height. The individual group regression equations for BV, DAN, SOC accounted for 87%, 79.5%, and 97.9% of the variance in drop jump height respectively.

Discussion

The primary purpose of this study was to identify how jump performances and joint stiffness are different among female athletic groups. The secondary purpose was to identify the potential relationship between joint stiffnesses and strength to jump performance. Our major findings were that hip stiffness during the loading phase was the only difference between athlete groups, which countered our hypothesis that joint stiffnesses would differ across populations. Also, female athletes in BV jumped higher with a greater impulse than dancers with more compliant hip during the loading phase than DAN. The SOC did not have difference in any variables of interest with either BV or DAN. For all female athletes combined, predictors of jump height were limited to hip concentric and knee eccentric isokinetic peak torques. However, the regression equation for individual female athletic groups included different predictors to the drop jump height.

The results partially support our hypothesis that there is a difference in jump height between athletes. The BV jumped higher than DAN, but there was no difference between the SOC group and any other group. The greater jump height in BV is possibly attributed to altered muscle properties induced by the greater plyometric training experience (Table 1). A 14-week plyometric exercise intervention increased jump height and ankle stiffness (Kubo et al., 2007), which was attributed with changes in properties of the active structure (Malisoux et al., 2006) with a lack of change in tendon stiffness (Kubo et al., 2007). The current study did not observe a greater ankle stiffness associated with plyometric training and higher jump heights in BV, which is most likely due to the normalization procedure of the joint stiffness with body mass unlike the previous study (Kubo et al., 2007). Body mass normalization was critical due to the differences found between groups allowing comparison of kinetic variables. Although our supplement analysis for the non-normalized ankle stiffness also had a significant difference ($t(24) = 2.762$, $p = 0.028$) between BV and DAN during the absorption phase, it is unclear whether the difference resulted from training effect or body mass.

Unlike our findings, volleyball and beach volleyball players have previously been shown to exhibit greater countermovement jump height than soccer players (Haugen et al., 2021). This disagreement is possibly caused by different athlete characteristics. Specifically, Haugen et al. (2021) recruited athletes from Norwegian national teams whereas the population of the present study is college athletes. Also, they simply compared jump height between two sports without considering sex differences despite greater jump height difference in males than females whereas we examined jump performance in female athletes. Lastly, they recruited pure volleyball and soccer players to measure jump performance whereas the present study combined volleyball and basketball players into a single group. It could be thought that the difference possibly results from the task difference, but a high correlation between countermovement jump and drop jump height has been found (Young et al., 1995).

An unexpected result was that BV had reduced hip stiffness during the loading phase as compared to DAN without difference in knee and ankle stiffness despite a greater jump height. Typically, knee and ankle stiffness have been connected to performance of other sports-related movements such as running (Kuitunen et al., 2002; Stefanyshyn & Nigg, 1998) and double-leg hopping (Kuitunen et al., 2011). Sprinters possess greater ankle (Stefanyshyn & Nigg, 1998) and knee stiffness (Kuitunen et al., 2002) than running at slower speeds. Additionally, by increasing knee stiffness, flight time during hopping was increased (Kuitunen et al., 2011). However, only one study (Hobara et al., 2010) examined hip stiffness by changes in hopping frequency in healthy males, and reported reducing hop frequency significantly increased flight time with reduced hip stiffness. The reduced hip joint stiffness with the increased flight time of hopping was caused by the increased hip angular displacement with the unchanged hip moment (Hobara et al., 2010).

However, in our study, the reduced hip stiffness in BV may be attributed to the negative hip stiffness caused by an increased hip external extension moment while hip flexion angle increased. As seen in Figure 5, the negative hip moment (i.e., external hip extension moment) was observed during the loading phase while all joints resist the external load eccentrically. A drop landing task demands athletes attenuate the momentum in the anterior direction after landing. This demand produced a negative hip moment as the vector of the resultant GRF pointed behind of hip joint center while the hip flexion angle is increasing. The line of best fit obtained by the 2nd order polynomial regression model using the different increasing directions of hip joint angle and moment has a concave shape, and the averaged tangent slopes of the line of best fit (i.e., joint stiffness of the subdivided phase) could be negative or positive value by the location of the vertex. Additionally, it was found that BV had a greater hip joint moment at IC ($t(24) = 2.916$, $p = .020$) than DAN in the supplement analysis, which caused the mean of the tangent slopes of the best fit line at the beginning of the loading phase in BV to be negative compared to the positive of DAN.

As seen in Table 5, the predictors that were entered into each group's regression equation differed in coefficients and significance. Even though female athletes may have distinct strategies to achieve jump height as a result of their sport-specific training, the potential distinct strategies could be offset when performing regression analysis for all female athletes as a single group. Specifically, although hip concentric and knee eccentric peak torques were predictors of drop jump height for the overall female athlete regression, each predictor was weighted differently for each individual female athletic group. Hip concentric peak torque was negatively weighted for both DAN and SOC groups but positively weighted for the BV group. Additionally, knee eccentric peak torque was a predictor of drop jump height in the DAN and SOC groups but not in the BV group. This result supports the hypothesis that female athletes possess different strategies to achieve their maximal jump height following a drop jump based on isokinetic strength.

The DAN group was the only group to include joint stiffness parameters in their regression equation. DAN relied on a hip and ankle dominant strategy to achieve their jumps in response to the external load. DAN athletes achieved their drop jump height by utilizing a stiffer hip during the loading phase and a more compliant hip and ankle during the absorption phase. It is possible that female athletes in the DAN group may change a major muscle-tendon unit storing the elastic energy during the eccentric phase. Specifically, the elastic energy could be stored in the triceps surae muscle-tendon units by fixing the proximal segment (i.e., thigh) during the loading phase. In contrast with the loading phase, the hip becomes compliant during the absorption phase so that the hip extensors could store the elastic energy to maximize the jump height. The hip dependence in DAN supports previous findings of the hip being the largest contributor to the peak total support moment of the lower extremity joints (Orishimo et al., 2009).

Although knee concentric peak torque has been shown to be a performance predictor in healthy males (DeStaso et al., 1997; Tsiokanos et al., 2002) and females (Tsiokanos et al., 2002), knee concentric peak torque was only a significant predictor of drop jump height only in the SOC athletes. When considering conflicted weights of hip and knee peak torques between eccentric and concentric strength (Table 5), SOC athletes may not transfer the elastic energy stored in hip extensors from the eccentric phase to the propulsive phase. Thus, they may rely on concentric knee strength than the joint stiffness to maximize drop jump height. Similar to the SOC athletes, BV athletes may utilize hip and ankle concentric strength for the drop jump height. However, unlike SOC and DAN athletes, BV athletes increased the drop jump height by the increased both ankle concentric and eccentric peak torques. Although ankle platarflexors are likely to play a crucial role to maximize the drop jump height when considering the coefficient of ankle eccentric peak torque, it was not reflected to the joint stiffness during the drop jump tasks. A possible explanation could be that the isokinetic strength test protocols do not represent the peak force production during the closed kinetic chain movement performed during the drop jump task, as the tests are performed with open-chain, single-joint isolated protocols (Blackburn & Morrissey, 1998). Since the peak force production is altered by positions of adjacent joints due to biarticular muscles such as gastrocnemius, quadriceps, and hamstrings (Ferris & Hawkins, 2020), the entered isokinetic peak torques might not be actually related to the jump performance.

The current study had a few limitations. First, due to the effect of the COVID-19 pandemic, the time of data collection for each group varied throughout the entire academic year and within times of their season. Specifically, volleyball players were recruited during their pre-season whereas soccer players and basketball players participated during their in-season and post-season periods, respectively. The dancers did not have an identified season, but saw a reduced workload due to the inability to hold performances. These differences in participation within their seasons, might have impacted their current physical fitness capacities, specifically power. Soccer players had better countermovement jump and sprint performance in the off-season as compared to pre-season (Haugen, 2018). Since the conditioning program typically covered both aerobic and anaerobic training, the performance of the explosive movement is likely reduced (Arcos et al., 2015; Haugen et al., 2021). Another limitation of this study is that basketball and volleyball players were allocated to the same group as the sample size was not sufficient to compare variables of interest between athletic groups as an independent group. Even though both sports require frequent jumping movements, volleyball is a more vertical-oriented sport as compared to basketball. Thus, the potential differences between basketball and volleyball players might be offset due to the combined them into a single group. Lastly, the stepwise regression equations for each group may be overfitted due to the small number of sample size in that a lot of predictors were included in each regression equation as compared to the overall equation. This limitation suggested that further study examine the joint stiffness strategy to maximize jump height with a large sample size.

In summary, the current study examined differences in drop jump performance and joint stiffness between female college athletes and the relationship between the performance and joint stiffness and isokinetic strength. Basketball/Volleyball players had a greater drop jump performance with more compliant hip during the loading phase than dancers, and soccer players did not have any difference in performance and joint stiffness as compared to both female athletic groups. Each athletic group had different joint dominance for drop jump performance, which is most likely induced by sports and training demands. However, the distinct joint dominance for each group was offset when predicting jump height for overall female athletes.

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Table 4.1. Demographic information (Mean ± SD)

	BV (n = 9)	DAN (n = 10)	SOC (n = 8)	F(2,24)	p	ES (ω^2)
Age (years)	20.4 ± 1.24	21.0 ± 2.75	20.0 ± 1.20	0.601	0.556	-0.030
Height (m)	1.83 ± 0.063*,†	1.69 ± 0.049	1.72 ± 0.056	16.869	< .001	0.540
Body Mass (kg)	74.0 ± 11.2*	59.5 + 5.66	64.4 ± 5.71	8.066	0.002	0.344
History of Resistance exercise (years)	6.33 ± 3.64*,†	0 ± 0	2.39 ± 1.74	18.120	< .001	0.559
History of plyometric exercise (years)	5.11 ± 4.51*,†	0 ± 0	0.25 ± 0.707	10.838	< .001	0.422

Note. BV = Basketball and volleyball, DAN = Dancers, SOC = Soccer, ES = Effect size.
* indicates significant differences between BV and DAN ($p < .05$).
† indicates significant differences between BV and SOC ($p < .05$).

Table 4.2. Jump height and jump impulse (Mean ± SD)

	BV (n = 9)		DAN (n = 10)		SOC (n = 8)		Team			Box	
	30 cm	60 cm	30 cm	60 cm	30 cm	60 cm	BV	DAN	SOC	30 cm	60 cm
Jump Height (m)[*]	0.306 ± 0.046	0.297 ± 0.052	0.233 ± 0.042	0.226 ± 0.032	0.266 ± 0.048	0.267 ± 0.047	0.302 ± 0.048	0.229 ± 0.037	0.266 ± 0.046	0.267 ± 0.054	0.262 ± 0.052
Jump Impulse (m/s)[*,†]	2.541 ± 0.212	2.492 ± 0.225	2.214 ± 0.168	2.181 ± 0.144	2.342 ± 0.208	2.337 ± 0.202	2.517 ± 0.213	2.197 ± 0.154	2.340 ± 0.198	2.631 ± 0.234	2.331 ± 0.227

Note. [*] indicates a significant greater jump height and jump impulse in BV than DAN ($p < .05$).
[†] indicates a significant greater jump impulse in 30 cm than 60 cm ($p < .05$).

Table 4.3. Vertical and joint stiffness during loading and absorption phases (Mean ± SD)

	BV (n = 9)		DAN (n = 10)		SOC (n = 8)		Team			Box	
	30 cm	60 cm	30 cm	60 cm	30 cm	60 cm	BV	DAN	SOC	30 cm	60 cm
Loading											
Hip (Nm/kg/°)*	0.012 ± 0.082	-0.136 ± 0.185	0.009 ± 0.399	0.420 ± 0.939	0.137 ± 0.198	0.208 ± 0.308	-0.062 ± 0.158	0.214 ± 0.733	0.173 ± 0.253	0.048 ± 0.267	0.172 ± 0.631
Knee (Nm/kg/°)	0.078 ± 0.019	0.103 ± 0.029	0.087 ± 0.099	0.048 ± 0.029	0.052 ± 0.037	0.049 ± 0.050	0.090 ± 0.027	0.068 ± 0.074	0.050 ± 0.043	0.074 ± 0.064	0.067 ± 0.044
Ankle (Nm/kg/°)	0.035 ± 0.017	0.039 ± 0.007	0.049 ± 0.052	0.038 ± 0.022	0.025 ± 0.013	0.030 ± 0.009	0.037 ± 0.126	0.040 ± 0.039	0.027 ± 0.011	0.035 ± 0.034	0.036 ± 0.015
Vertical (BW/m)†	26.371 ± 15.919	34.847 ± 12.156	36.242 ± 19.479	37.046 ± 13.349	27.317 ± 12.137	37.471 ± 14.282	30.609 ± 14.416	36.644 ± 16.258	32.394 ± 13.836	30.307 ± 16.451	36.439 ± 12.783
Absorption											
Hip (Nm/kg/°)	0.132 ± 0.143	0.052 ± 0.099	-0.240 ± 0.932	-0.021 ± 0.250	0.021 ± 0.148	0.063 ± 0.066	0.092 ± 0.117	-0.130 ± 0.674	0.042 ± 0.113	-0.039 ± 0.581	0.028 ± 0.165
Knee (Nm/kg/°)	-0.013 ± 0.025	-0.027 ± 0.020	-0.004 ± 0.027	-0.021 ± 0.021	0.001 ± 0.021	-0.008 ± 0.013	-0.020 ± 0.023	-0.013 ± 0.025	-0.004 ± 0.017	-0.005 ± 0.024	-0.019 ± 0.019
Ankle (Nm/kg/°)	0.045 ± 0.030	0.033 ± 0.022	0.017 ± 0.049	0.010 ± 0.018	0.023 ± 0.042	0.061 ± 0.060	0.039 ± 0.026	0.014 ± 0.036	0.042 ± 0.054	0.028 ± 0.042	0.033 ± 0.041
Vertical (BW/m)	-0.667 ± 3.066	-4.109 ± 7.055	-19.680 ± 61.672	-9.098 ± 23.687	-0.638 ± 6.354	0.413 ± 1.638	-2.388 ± 5.566	-14.389 ± 45.792	-0.113 ± 4.515	-7.700 ± 37.656	-4.617 ± 15.028

Note. * indicates a significant greater stiffness in DAN than BV ($p < .05$).

† indicates a significant greater stiffness in 60 cm than 30 cm ($p < .05$).

Table 4.4. Isokinetic concentric and eccentric peak torques of lower extremity joints (Mean ± SD)

	BV (n = 9)	DAN (n = 10)	SOC (n = 8)	$F(2,24)$	p	ω^2
Hip Con Ext (Nm/kg)	2.658 ± 0.813	2.417 ± 0.803	2.166 ± 0.541	0.930	0.410	-0.005
Hip Ecc Ext (Nm/kg)	3.374 ± 0.938	3.299 ± 1.074	3.432 ± 0.913	0.041	0.958	-0.076
Knee Con Ext (Nm/kg)	1.378 ± 0.559	1.177 ± 0.554	1.622 ± 0.672	1.253	0.302	0.019
Knee Ecc Ext (Nm/kg)	2.431 ± 0.954	2.740 ± 0.693	2.399 ± 0.941	0.450	0.643	-0.043
Ankle Con PF (Nm/kg)	1.073 ± 0.549	1.061 ± 0.378	0.856 ± 0.410	0.618	0.548	-0.029
Ankle Ecc PF (Nm/kg)	1.403 ± 0.399	1.482 ± 0.247	1.310 ± 0.501	0.443	0.647	-0.043

Note. Con = Concentric isokinetic strength test, Ecc = eccentric isokinetic strength test, Ext = Extension, PF = Plantarflexion.

Table 4.5. Stepwise regression models for each team and overall female athletes

	BV		DAN		SOC		Overall	
	β	*t*	*β*	*t*	*β*	*t*	*β*	*t*
Intercept	0.175*	3.863	0.628*	9.800	0.305*	26.574	0.206*	7.915
Hip Loading (Nm/kg/°)	0.078	1.987	0.028*	2.999				
Hip Absorption (Nm/kg/°)			-0.074*	-3.798				
Knee Loading (Nm/kg/°)	0.317	1.113						
Knee Absorption (Nm/kg/°)	-0.251	-0.895	0.699	1.837			-0.549	-1.860
Ankle Loading (Nm/kg/°)	0.455	1.069	-1.121*	-2.962				
Ankle Absorption (Nm/kg/°)	0.23	0.924			-0.056	-1.664		
Hip Con Ext (Nm/kg)	0.091*	5.084	-0.027*	-2.245	-0.144*	-15.366	0.030*	2.358
Hip Ecc Ext (Nm/kg)	-0.231*	-3.208	0.054*	4.415	0.097*	12.746		
Knee Con Ext (Nm/kg)	0.067	1.411			0.157*	17.486	0.021	1.364
Knee Ecc Ext (Nm/kg)	0.010	0.874	-0.061*	-4.263	-0.040*	-7.355	-0.019*	-2.069
Ankle Con PF (Nm/kg)	0.052*	3.532	-0.062*	-2.753	-0.222*	-23.723		
Ankle Ecc PF (Nm/kg)	0.312*	2.783	-0.152*	-6.152	-0.021*	-3.140		
F	11.348		9.164		102.45		4.221	
p	0.004		0.001		<.001		0.005	
r^2	0.954		0.892		0.989		0.256	
adjusted r^2	0.870		0.795		0.979		0.196	

Note. * indicates significant independent variables in the regression model ($p < .05$).
Con = Concentric isokinetic strength test, Ecc = eccentric isokinetic strength test, Ext = Extension, PF = Plantarflexion.

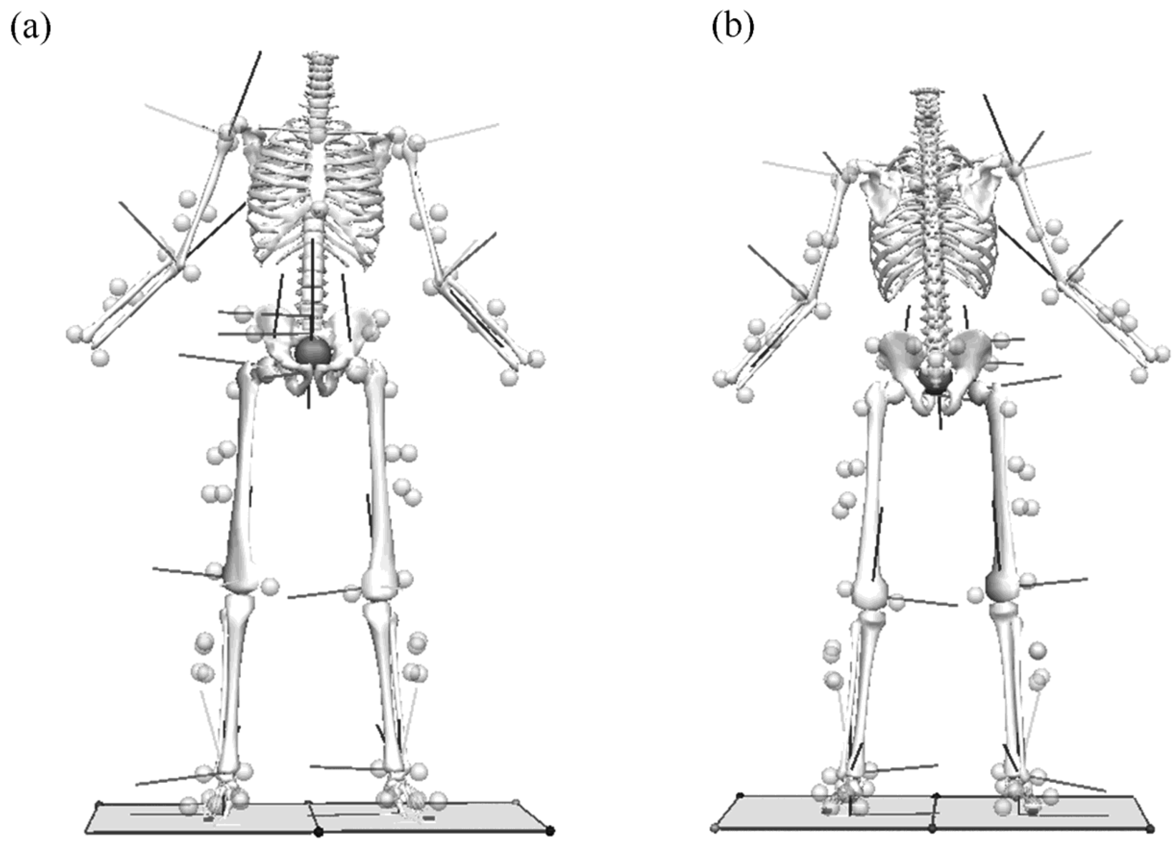

Figure 4.1. The front (a) and back (b) of a customized full-body marker set.

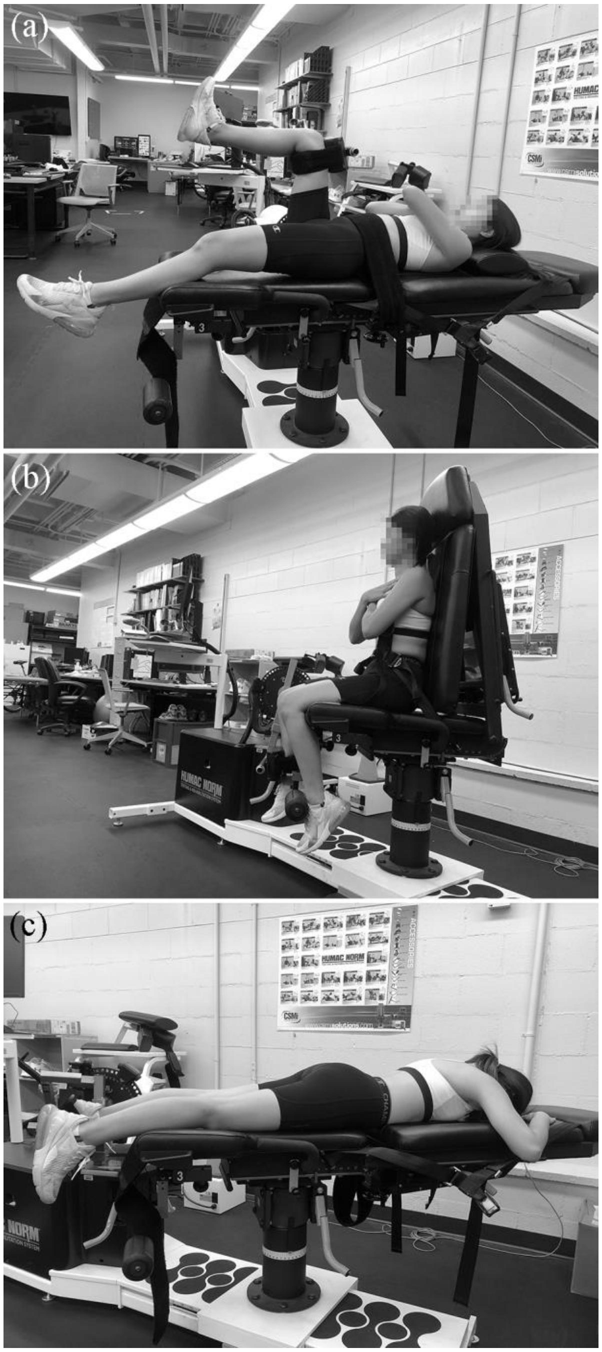

Figure 4.2. Concentric and eccentric isokinetic strength tests. (a) Hip extension in supine position, (b) knee extension in sitting position, and (c) ankle plantarflexion in prone position.

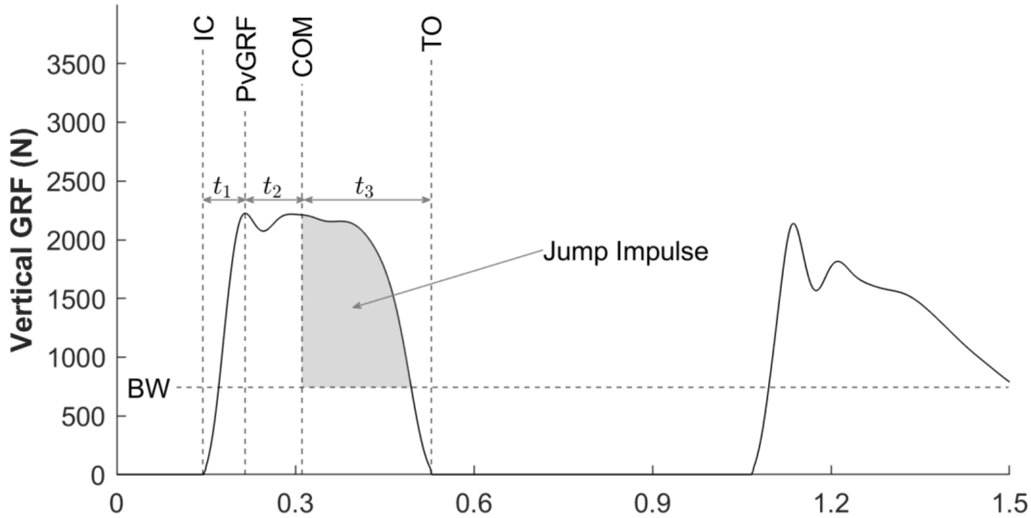

Figure 4.3. Jump impulse. BW: Body weight; IC: Initial contact; PvGRF: Peak vertical ground reaction force; COM: The time frame of the center of mass (COM) positioned at the lowest position; TO: take-off; t_1: duration of the loading phase; t_2: duration of the absorption phase; t_3: duration of the propulsive phase.

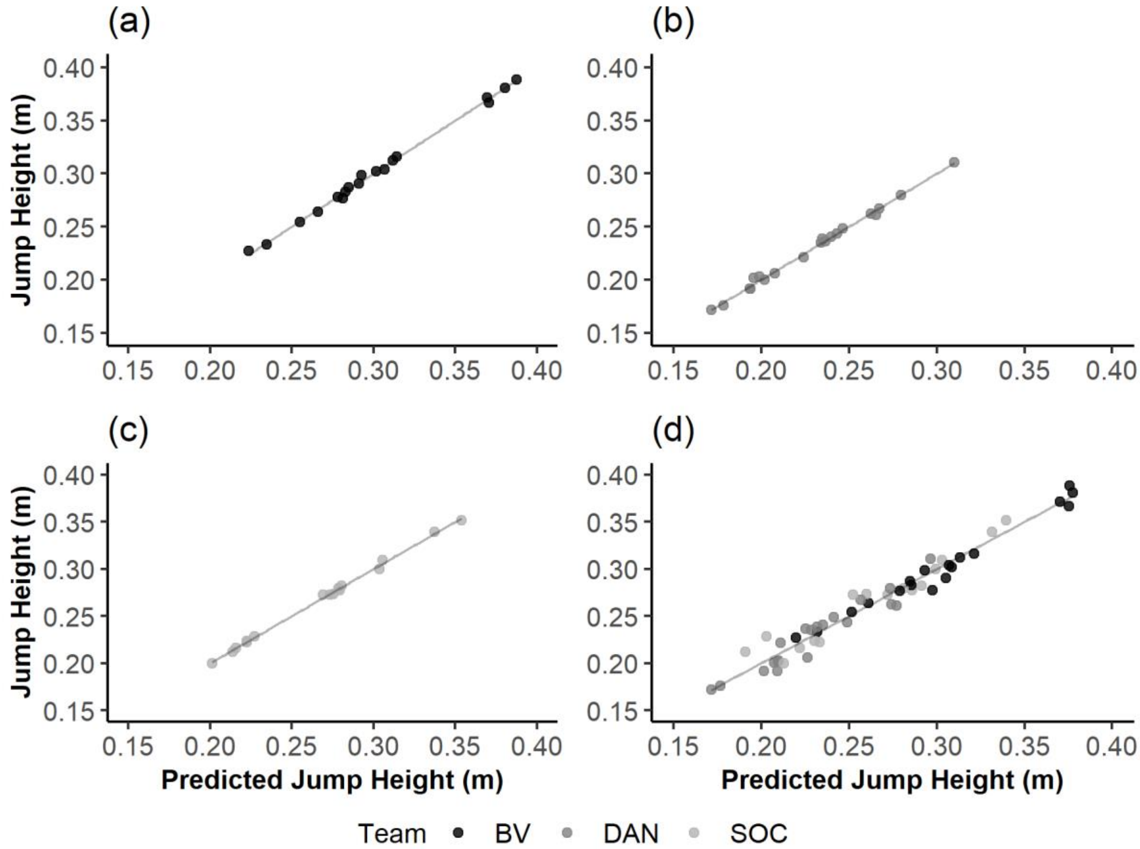

Figure 4.4. A scatter plot of the jump height and estimated jump height by the regression equations for (a) BV, (b) DAN, (c) SOC, and (d) overall female athletes. BV: Basketball/Volleyball; DAN: Dance; SOC: Soccer.

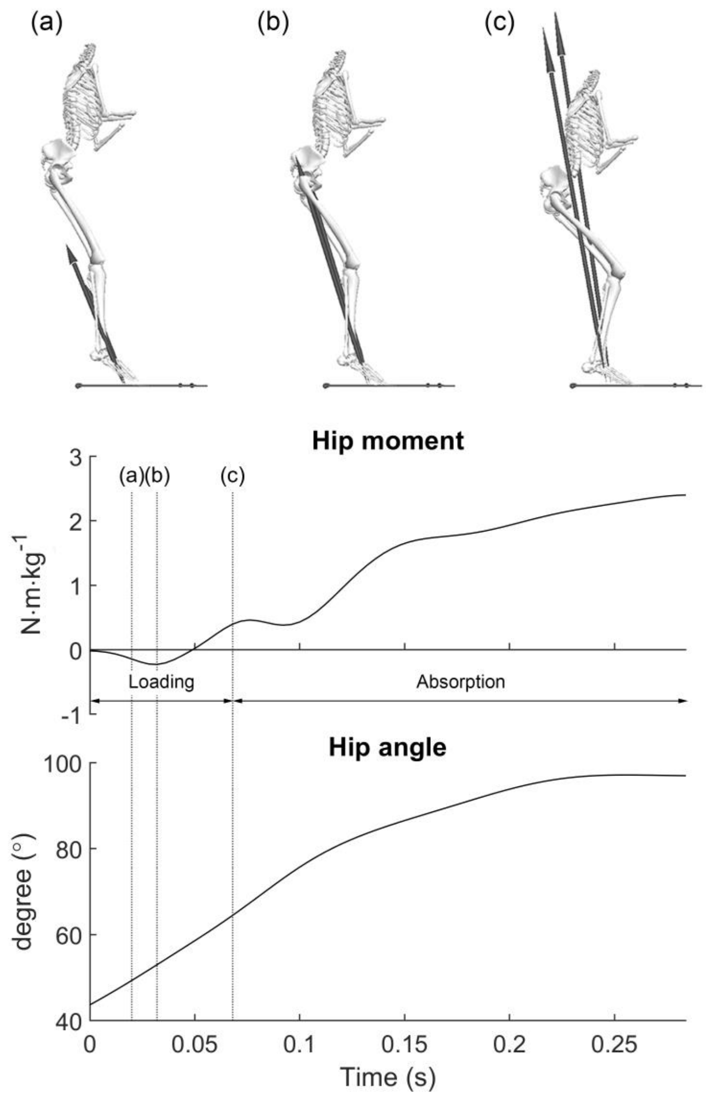

Figure 4.5. The changes in the hip joint angle and moment by the direction of the resultant GRF vector during the eccentric phase of the drop jump. (a) 20 ms after IC, (b) minimum hip joint moment, and (c) the end of the loading phase (i.e., at peak vertical ground reaction force).

Chapter 5: Conclusion

The overall purpose of this dissertation was to investigate the potential relationship between joint stiffness and drop jump performance among different populations using a novel method to calculate joint stiffness. The first major finding was that 2^{nd} order polynomial regression was a more accurate representation of the moment-angle curve during the drop jump task than the traditional linear regression model and therefore should be used to calculate joint stiffness. It was found that female collegiate athletes successfully complete the task by engaging different stiffness and isokinetic strength measure. This result was shown from the differences in their regression equation and is thought to be a result of different sport demands and training.

The traditional approach to calculating joint stiffness was to mathematically apply a linear regression model to fit the joint angle-moment relationship. Additionally, in tasks such as the drop jump, the eccentric phase has been commonly analyzed as a single phase. The focus of the first study in this series was to demonstrate the potential benefit of using a 2^{nd} order polynomial to calculate stiffness and the rationale of dividing the eccentric phase into two subphases. This novel method was able to represent the joint angle-moment curve more accurately in both eccentric subphases (i.e., loading and absorption). The polynomial model was more robust than the linear model in the ability to detect changes in joint stiffness throughout the eccentric phase. The findings from this analysis demonstrated the need to further divide the eccentric phase into smaller sub phases (loading and absorption) citing electromechanical delays may cause the muscle-tendon structure to respond differently to loads within each of the subphases. Also, it is suggested that the 2^{nd} order polynomial regression model should be used to calculate joint stiffness in order to understand changes in joint stiffness for absorption and transmission of the external load for the subsequent task.

By investigating the angle-moment relationship with the polynomial regression, the second manuscript attempted to identify sex differences in drop jump performance and joint stiffness. Additionally, the potential relationship between the jump performance and stiffness measures were investigated. Healthy and active males achieved a greater drop jump height that was accomplished with a stiffer hip and ankle during the loading phase and knee during the absorption phase. The effects of body mass were removed as the moments were normalized, removing the potential effect of body mass. Also, males and females achieved their maximal drop jump height using different joint stiffness strategies. Males did not manipulate joint stiffness during the subphases of the eccentric phase whereas females increased not only hip but also knee stiffness during the loading. These different joint strategies between males and females for the jump performance suggests a necessity of developing separate training protocols for each sex to improve jump performance. Additionally, different strategies between males and females might contribute to leading the difference in a specific sports injury especially related to knee joint. The inclusion of hip stiffness as a predictor in max jump height indicates the importance of the gluteus muscles which are major force producers during hip extension and eccentric loading. The hip is also the most proximal joint in the kinetic chain using triple extension technique to achieve maximal jump height. The inclusion of knee stiffness for females could be related to a more quadricep dominant strategy, which are the major eccentric muscle to oppose knee flexion as well as a stabilizer for the knee. The quadriceps muscles also provide stress to the anterior cruciate ligament by anterior translation during shallow knee flexion. It is hypothesized that given the range of motion of the knee during the loading phase, the combined hip and knee stiffness components in females contribute to the sex differences in increased risk of anterior cruciate ligament injuries. Therefore, future studies need to evaluate the effect of training protocols to improve specific joint stiffness on the jump performance for each male and female. Longitudinal observations of sports injury occurrences in females who have greater knee stiffness to achieve maximal jump height will provide further connection to this potential relationship.

To further understand the relationship between joint stiffness and jump performance, it is important to investigate what differences in sport specific training and training history have on female athlete performance. It was hypothesized that females would have different strategies of coordinating joint stiffnesses of the lower extremity to achieve the drop jump task due to the sport specific training demands. Certain sports require athletes to focus on jumping maximally or landing with fluidity, while others place greater demand on speed and cutting maneuvers. Specifically, female basketball and volleyball athletes have a higher demand on vertical jump mechanics and are exposed to greater amounts of plyometric training than many other female athletes because of this demand. Dance athletes experience a high volume of leaps and jumps; however, their goal is not to achieve maximal height or power. Traditionally the type of weightlifting and plyometric training designed to enhance the stretch-shortening cycle are limited in dancers. Female soccer athletes have low demand for jumping with a high demand on explosive cutting mechanics, which creates a torsional and frontal plane stress on the joint of the lower extremity. Thus, the final study examined in jump performance and joint stiffness between groups of female collegiate athletes (Basketball/Volleyball: BV, Dancers: DAN, Soccer: SOC) and to identify the relationship between drop jump performance and both joint stiffness and isokinetic strength. It was found that female basketball and volleyball athletes had greater drop jump height, jump impulse, and reduced hip stiffness during the loading phase than dancers. Also, female athletes possessed different joint dominance while completing the drop jump task. It should be highlighted that the findings were not in line with previous research stating that the ankle joint stiffness increase linearly with jump performance. Some of the athletes in this study used a compliant ankle which may optimize the storage of elastic energy within the gastrocnemius and Achilles' tendon. Therefore, further research is necessary to examine the interaction of lower extremity joint stiffness in terms of the jump performance in female basketball/volleyball players and dancers.

Due to the effect of COVID-19 pandemic throughout the second data collection, it was challenging to recruit sufficient numbers of female volleyball and basketball players. Thus, female volleyball and basketball players were allotted to the same group for the third manuscript despite potential sport demand differences, specifically their jump task differences. This group allocation might induce offsetting the potential differences between volleyball and basketball, as well as some of the other groups. Also, the muscle activation levels during drop jump tasks were measured by electromyography for the third manuscript, but the data were not analyzed due to the synchronization issue. Therefore, to identify further differences in joint stiffness and the source of different joint dominance among female athletes, future studies need to recruit greater number of female athletes for group allocation to each individual sport and measure the muscle activity.

The results suggest that when calculating joint stiffness during the drop jump task, as well as other tasks that involve a curvilinear relationship between the joint angle and moment, stiffness should be calculated using a 2nd order polynomial. It is also suggested that the eccentric phase should be subdivided into the loading and absorption phases in accordance with the appearance of peak vertical ground reaction force as the muscle-tendon structures behave differently in response to the mechanical demands. With respect to jump height, differences between sex and athlete-specific populations were found. Within female athletes, we found that those who have greater jump height, maximized their jump height by utilizing a compliant ankle with stiff knee. This is the biggest finding in this dissertation and refutes the hypothesis of the linear relationship between ankle stiffness and sports performance.

Appendix A - Informed Consent of the first data collection

Informed Consent
University of Idaho
Department of Movement Sciences

Title: Gender Differences in Joint Coordination during Drop Jump
Investigator: Joshua Bailey, PhD
University of Idaho
Department of Movement Sciences
Moscow, ID 83844
Ph: 702-406-7470
e-mail: joshuabailey@uidaho.edu

The University of Idaho's Institutional Review Board has approved this project.

Purpose of study:
You are invited to participate in a research study in the Department of Movement Sciences at the University of Idaho. The purpose of this study is to investigate the gender differences in joint coordination during drop landing tasks.

Participants:
You are being asked to participate in this study because you fit the following criteria:

- Your age is between 18 and 64 years old.
- You either engage in moderate-intensity physical activity for a minimum of 30 minutes - 5 days a week, or vigorous-intensity physical activity for a minimum of 20 minutes -3 days a week.
- You have not had lower back pain and lower extremity musculoskeletal injury over the past year.
    - The musculoskeletal injury (i.e., sprain, muscle tear, fracture) is the case if you were not able to participate in the physical activation at least two consecutive days due to the pain or disability of movement.
- You have not had surgery on your lower extremity, lower back, or pelvic girdle.
- You are not pregnant, nor do you think you are pregnant.
- If you are female, your data collection schedule may be changed according to your menstrual cycle because the menstrual cycle can increase joint laxity. The data collection will be conducted within 10 days after the end of period.

Procedures:

1. You will be asked to complete all tasks during 1 session. Prior to begin the data collection, you will be asked to answer questions to determine if you are eligible to participate in this study.

If you are eligible to participate in the study and are willing to participate, you will be asked to complete the following:

2. You will be asked to wear the following clothing:
    a. Male: Spandex shorts and no shirts.
    b. Female: Spandex shorts and sports bra (or tight thank top).

   c. If you do not feel comfortable in the requested clothing, we can discuss possible alternatives.
3. One of the research members will measure your demographic information such as age, gender, height, mass, and dominant leg (i.e., mainly used leg when you kick a ball).
4. You will be asked to warm-up for at least 5 minutes. The warm-up could be comprised of (but not limited to) stretching, dynamic warm-ups, riding a bike or a combination of any of these.
5. Following the warm-up, you will be instrumented with a number of reflective markers which will be attached to your body via a combination of tapes and wraps. This is why we have requested you to wear the clothing that is tight and limited.
6. You will be asked to complete a series of drop jumps from two box heights (30 & 60 cm).
   a. You will be asked to jump off the box, land within the target area, and then vertically jump up as high as you can, as quickly as you can.
   b. You will be provided at least 2 practice trials at each box height, with as many as 5 practice trials allowed.
   c. We will record 15 successful trials with as much time between jumps as needed.
   d. A trial is deemed not successful if you fail to land within the target area and if you lose your balance.
7. Following the completion of the drop jump tasks, all markers and tapes will be removed from your body.

Benefit of participation:

- There will be no direct benefit for you participating in this study.
- You may learn your altered landing mechanics and/or strategy according to the changes in the box height by yourself.

Risk of participation:

There are risks involved in all research studies. This study may include minimal risks. The possible minimal risks include muscle fatigue/soreness from repeated drop jump tasks, as well as the possibility of rubbing/discomfort from the attachment of markers.

While you are testing, there might be other people in the laboratory who are not part of our research team. They may be observing data collection or collecting data for another study. There is the risk that you may feel uncomfortable with other people in the laboratory. We try to minimize this risk by allowing access to the lab by people who have a specific need (e.g. data collection for another project, etc.).

Confidentiality:

All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. If you give permission for videotaping/photography, we may use your images and motion capture images for presentation purpose. All physical and personal identifiers will be removed from all prior to use.

Voluntary Participation:

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with U of I and the research members. You are encouraged to ask questions about this study at the beginning and any time during the research study.

Participant Consent:

I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

Signature of Participant: Date:

Participant Name (Please Print):

Videotaping/Photography:
I agree to be videotaped or photographed for the purpose of this research study. Video/pictures may be used in presentations/publications, but no identifying features will be shown.

Signature of Participant: Date:

Participant Name (Please Print)

Appendix B - Informed Consent of the Second Data collection

Informed Consent
University of Idaho
Department of Movement Sciences

Title: Joint stiffness and muscle activations in female athletes
Investigator: Joshua Bailey, PhD
University of Idaho
Department of Movement Sciences
Moscow, ID 83844
Ph: 702-406-7470
e-mail: joshuabailey@uidaho.edu

The University of Idaho's Institutional Review Board has approved this project.

Purpose of study:
You are invited to participate in a research study in the Department of Movement Sciences at the University of Idaho. The purpose of this study is to investigate differences in lower extremity joint stiffness and muscle activation between female collegiate athletes. Additionally, we will look to investigate the relationship between lower extremity stiffness and muscle activation across athletes.

Participants:
You are being asked to participate in this study because you fit the following criteria:

- Your age is between 18 and 28 years old.
- You are in one of the following athletic teams or dance program on the UI/WSU campuses
  - Basketball team
  - Track & Field team
  - Female volleyball team
  - Female soccer team
  - Dance program (ballet-trained)
- You are currently engaging in all team practice and able to perform repetitive jump and landing movements without pain even if you have surgery on your lower body or low back (i.e., Anterior cruciate ligament reconstruction, etc) before.
- If you have current injuries on your lower extremity or low back (i.e., sprain, strain, fractures, overuse injuries, etc.), you won't be able to participate in this study.

Procedures:

8. *Preparation*
   a. You will be asked to complete all tasks during 1 session. The session consists of eccentric isokinetic strength tests and 3D motion capture during drop jumps.
   b. Prior to beginning the data collection, you will be asked to answer questions to determine if you are eligible to participate in this study.
   c. If you are eligible to participate in the study and are willing to participate, you will be asked to wear spandex shorts and sports bra (or tight thank top).
      i. If you do not feel comfortable in the requested clothing, we can discuss possible alternatives.
   d. One of the research members will measure your demographic information such as age, gender, height, mass, and preferred leg.
   e. You will be asked to warm-up for at least 5 minutes. The warm-up could be comprised of (but not limited to) stretching, dynamic warm-ups, riding a bike or a combination of any of these. This will be self-selected, and you have the choice to perform any manner of warm-up you wish.

f. A total of 14 electromyography (EMG) sensors will be attached to your lower limbs on both sides. This process requires the researcher to shave, abrade and clean each site of sensor application. The sensors will then be applied using double-sided tape and further secured with cover-roll tape.
    i. Tibialis anterior (on the anterior side of your lower leg)
    ii. Soleus (on the medial side of your lower leg)
    iii. Gastrocnemius (on the posterior side of your lower leg)
    iv. Rectus femoris (on your quadriceps)
    v. Biceps femoris (on your hamstring)
    vi. Gluteus medius (on the right above your hip joint)
    vii. Gluteus maximus (on your buttock)
    viii. Please let us know if you are uncomfortable for attaching EMG sensors by male researcher when you are reviewing the informed consent. We will schedule female researcher for applying EMG sensors.

9. *Eccentric Isokinetic Strength Tests*
    a. Eccentric isokinetic strength tests of hip, knee, and ankle joints will be performed.
    b. You will be asked to sit on the isokinetic machine for the following tests.
        i. Hip flexion/extension (90°/sec)
        ii. Hip abduction (100°/sec)
        iii. Knee flexion/extension (180°/sec)
        iv. Ankle dorsi-/plantarflexion(100°/sec)
    c. All tests will be conducted at the angular velocities that are commonly recorded in the deceleration phase of the drop jump.
    d. The practice trials (3 repetitions) for each test will be provided for participants to be familiar with the isokinetic machine.
        i. Following the practice trial, at least a 30-second break will be given.
        ii. The longer break will be provided if needed.
    e. Following the rest, you will be asked to conduct 3 maximal effort test trials per condition.

10. *3D motion captures*
    a. Following the isokinetic strength test, you will be instrumented with a full-body reflective marker set.
        i. Reflective markers will be attached to each body segment using a combination of tapes and wraps. Please let a researcher know if you have an allergy to adhesives. Most of the tapes are surgical grade and non-latex, but we will make sure to not use the others if you have an allergy.
    b. You will perform the drop jump and drop landing from 30 cm and 60 cm boxes.
        i. Drop Jump
            1. The boxes will be positioned as far as half of each participant's height from two embedded force platforms.
            2. You will be asked to stand at the edge of the box and drop off from the box.
            3. You will be instructed to land on the force platforms and then perform a maximal vertical jump immediately.
        ii. Drop Landing
            1. The boxes will be positioned as far as half of each participant's height from two embedded force platforms.
            2. You will be asked to stand at the edge of the box and drop off from the box.
            3. You will be instructed to land on the force platforms and then maintain a standing posture for a second.
        iii. At least 30 seconds break will be given between trials.
            1. A longer break will be provided if needed.
    c. You will have at least 2 practice trials at each box height, with as many as 5 practice trials allowed.
    d. A total of 3 good trials will be collected. If you go beyond 5 attempts to achieve the 3 good trials at a particular height, you will be stopped from that height and asked to perform the next test.
        i. The trial will be deemed to a 'not good trial' if you ...

1. jump up when they drop off from the box
2. land out of the force platforms
3. do not perform a vertical jump immediately

11. Following the completion of the drop jump tasks, all markers and tapes will be removed from your body.

Benefit of participation:

- There will be no direct benefit for you participating in this study.
- The result of isokinetic strength test will be provided for you if you wish to know the results.
- Additionally, if you are interested in understanding what your jumping and landing mechanics (form) look like, we can review those with you.

Risk of participation:
There are risks involved in all research studies. This study may include minimal risks. The possible minimal risks include muscle fatigue/soreness from repeated drop jump tasks, as well as the possibility of rubbing/discomfort from the attachment of markers.

While you are testing, there might be other people in the laboratory who are not part of our research team. They may be observing data collection or collecting data for another study. There is the risk that you may feel uncomfortable with other people in the laboratory. We try to minimize this risk by allowing access to the lab by people who have a specific need (e.g. data collection for another project, etc.).

The majority of the tapes that are used for data collection are latex free. If you have an allergy to adhesives, please inform the research team to ensure that the proper tapes are used for your data collection. There is the possibility that you have a slight reaction to the rubbing of the tape on your skin.

Confidentiality:
All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. If you give permission for videotaping/photography, we may use your images and motion capture images for presentation purpose. All physical and personal identifiers will be removed from all prior to use.

Voluntary Participation:
Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with U of I and the research members. You are encouraged to ask questions about this study at the beginning and any time during the research study.

Participant Consent:
I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

________________________________ ____________________

Signature of Participant: Date:

____

Participant Name (Please Print):

Videotaping/Photography:
I agree to be videotaped or photographed for the purpose of this research study. Video/pictures may be used in presentations/publications, but no identifying features will be shown.

Signature of Participant: Date:

Participant Name (Please Print)

Appendix C - Chapter 2 Article Copyright

The article of Chapter 2 titled "Application of Polynomial Regression Model for Joint Stiffness" is an Author's Original Manuscript of an article submitted for consideration in *International Journal of Exercise Science*; *International Journal of Exercise Sciences* is available at: https://digitalcommons.wku.edu/ijes/

Appendix D - Chapter 3 & 4 Article Copyrights

The article of Chapter 3 titled "Differences in Lower Extremity Joint Stiffness during Drop Jump between Healthy Males and Females" and Chapter 4 titled "Differences in Jump Performance, Joint Stiffness, and Isokinetic Strength between Female athletes and Ballet-trained Dancers" are Author's Original Manuscripts of an article submitted for consideration in *Journal of Sports Sciences* [copyright Taylor & Francis/society]; *Journal of Sports Sciences* is available at: https://www.tandfonline.com/toc/rjsp20/current