THE EFFECT OF FATIGUE ON SUB-SYSTEM JOINT WORK:

THE INFLUENCE OF SEX, STRENGTH, AND ECCENTRIC LOADING

A Thesis
by
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Abstract

THE EFFECT OF FATIGUE ON SUB-SYSTEM JOINT WORK: INFLUENCE OF SEX, STRENGTH, AND ECCENTRIC LOADING

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Joint work distribution is an essential component to organismal locomotion. Typically expressed in forms of positive, negative, and net work, energy is dispersed or transferred through each joint and can be affected by changes in force conditions, sex, and fatigue. With increasing eccentric loads on the lower body, female and weaker individuals have been found to utilize a significantly higher amount of negative work in the knee, whereas males and stronger individuals have been found to utilize more positive work in the hip (McBride & Nimphius, 2020). These trends have yet to be investigated in fatigued subjects. The purpose of the current study was to evaluate the effect of fatigue on sub-system joint energy algorithms in the hip, knee, and ankle among healthy adults, while taking into consideration differences in strength and sex. Males and females were recruited to complete a countermovement jump (CMJ) and a series of drop jumps from 15 cm, 30 cm, 45 cm, 60 cm, and 75 cm (DJ15, DJ30, DJ45, DJ60, DJ75) using a VICON marker system and force plates. Subjects performed the jump protocol twice with a fatiguing protocol in the middle. Positive, negative, and net work were calculated for each subject in each jump trial, and data was evaluated based upon sex (M, F) and strength striations (LS, HS). Results showed significant differences in ankle, knee, and hip work between jump types within groups, but no statistically significant differences across groups. The fatiguing protocol produced a higher variability between jump types, but no significant differences in pre to post fatigue. The results of the current study have implications for future injury prevention and endurance-based sporting event research.

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Table of Contents

List of Tables

List of Figures

Introduction

Motion is propelled by the efficient transfer of energy among the system's components. Any motion performed by a modern vertebra can be summarized by energy that is transferred from the ground reaction force (GRF) produced with each step that is moved through the muscles, ligaments, and tendons to either be stored or propelled into action (Richards et al., 2013)Within this system, the joints act as checkpoints that either disperse the energy as heat or transport the energy to the next joint in the kinetic chain. With an infinite number of variations in organisms and their anatomy, the motions required for locomotion, and the conditions with which they complete them, each singular motion will have a different joint work distribution (Kargo et al., 2002). Preliminary investigations of these relationships have been completed using animal models. By utilizing animals who are prone to jumping, such as frogs and wallabies, researchers have begun to estimate what conditions create the most efficient jump. When applying these principles to humans, many models approximate the most efficient system for standing, walking, running, and jumping as one that utilizes 3 degrees of freedom (the ankle, knee, and hip) (Kargo et al., 2002). These models, however, differ greatly amid different conditions, motions, ages, and sexes (Alexander et al., 2017; Biewener & Daley, 2007; Bonnet et al., 2021; Sekulic et al., 2013) . Differences in sex are a variable that is easily controlled for. It has been well researched that males and females have different joint work distribution strategies during walking, running, descending a flight of stairs, and jumping, as males, who are typically stronger than females, utilize a hip-dominant model of joint distribution, whereas females tend to utilize a knee-dominant model (Hong & Shin, 2015; Kerrigan et al., 1998; Obrębska et al., 2020; Sakaguchi et al., 2014; Vannatta et al., 2020; Wünschel et al., 2013) . Potential causes for these differences include variations in muscle physiology, neurological signaling, and anatomical structure (Clark et al., 2005; Hunter et al., 2004; Merchant et al., 2020; Wünschel et al., 2013).

Fatigue, defined as the process in which maximal force production is decreased with repeated muscle activity, could also have an effect on joint work distribution. From a physiological standpoint, fatigue occurs via the depletion of easily accessible energy systems, triggering the anaerobic response. This anaerobic response causes a buildup of lactate and potassium, affecting the action potential necessary to initiate muscular contraction by decreasing blood pH. While the application of fatigue on total joint work is well researched, it is not well understood how fatigue affects joint work distribution between sexes with increasing force demands. The current study evaluated the effects of fatigue on joint work distribution between sexes and strength differences in humans. By assessing these differences, researchers will gain further knowledge on the nuanced energy transfers in individuals among sexes and strength differences and be able to apply these findings to rehabilitation protocols.

The energetics of muscle force production described above create the locomotive spectrum of all living things and can be summarized by a series of energy algorithms set to optimize power and efficiency of movement. These algorithms define the biomechanical capacity of the performer. A joint system's efficiency is maximized when there is a consistent flow of energy between its possible forms (kinetic, potential, and stored elastic energy) expressed through positive and negative work. Energy within the body is comprised of both tissue viscoelasticity, in which tendon and ligament elasticity dictates energy storage or dissipation, and muscle action, fueled by the alpha or beta chemical bond of adenosine triphosphate. As this energy flows through the muscle and tendon structures and maximum efficiency is attempted, performance and mechanical economy are measured via the balance of positive and negative work done on the center of mass (COM) of an object during the stretch-shortening cycle. As such, the delicate balance of these solutions can be altered via any host of variables when the conditions of the movement are changed, and the body is in peril. It has been shown that as force demands increase, the body will alter joint work distribution as a protection mechanism to prevent injury (McBride & Nimphius, 2020). Upon losing balance, humans produce greater negative work in both the knee and ankle than while walking on even ground as they attempt to recover. This increase in negative work allows the knee and ankle to provide sagittal and transverse stability, while increasing response time (Nagano et al., 2015). During more complex motions such as jumping, where force is produced and transferred through multiple joints, the lower-limb energy distribution overcompensates for unexpected force stimuli by excessively dissipating mechanical energy. This response is characterized by significant increase in peak negative power in the hip, knee, and ankle joints as well as significant increases in net negative knee power and total hip power (Dick et al., 2019).

Animal models are a useful tool to better understand energy algorithms and their response to increasing force demands. Organisms with higher net work values utilize spring driven model systems, in which more negative work is produced and energy is recycled back into the tendons. With little to no change in muscle fiber length while producing force, wallabies exhibit almost exclusively isometric behavior while hopping, with primary work produced by the most distal joints acting as springs (Biewener, 1998). This model utilizes isometric contractions to increase levels of negative work, as the organism attempts to improve its efficiency by recycling energy. This model would shift, however, to a motor-driven system if the wallaby were being hunted, as this system is more efficient at producing positive work. Frogs leverage the spring force produced by negative work to jump up to 1.6 times their body length by utilizing the elastic energy from the most distal joint to keep the hindlimbs on the ground for a longer period of time, which gives them more time to produce a higher GRF (Kargo et al., 2002).

In contrast, the pigeon while flying produces great muscle fiber length changes, completing a concentric contraction while producing the primary source of positive work in the most proximal joint (Biewener, 1998). In this motor driven system, the greatest rate of change in muscle fiber length occurs during the upstroke phase, which is comparable to the swing phase of human gait and produces high levels of positive work to keep in flight. These models help one better understand analyses for human motion. While walking on even ground, the human ankle joint contributes between 40 and 62 percent of the total lower body positive joint work, while the knee joint contributes between 17 and 28 percent, and the hip joint contributes between 18 and 32 percent of the lower body's total positive joint work (Bonnet et al., 2021). Work is the product of force and displacement, and in compound movements such as jumping, this work is distributed among the ankle, knee, and hip joints. As a jumping motion is completed, these values will vary based on the individual and their strength, power, balance, and adaptation capabilities. A perfectly balanced motion would produce a zero net work, but with the aforementioned categories, jumping will lead to a non-zero value as excess positive and negative work are produced in order to create the appropriate movement solution. This balance of negative to positive work can be characterized by a work loop, in which a force-displacement curve is plotted and the area underneath the curve is calculated (McBride & Nimphius, 2020). Principal component analysis (PCA) was used to quantify a human's most effective jumping models of the lower body and found two primary models. These results found that human jumping is governed by two degrees of freedom in the sagittal plane rather than three, and the most efficient models are comprised of one with greater loading in the hip and knee joint moments, and the other with greater loading in the ankle joint moment (Cushion et al., 2019). From these results, one can conclude that uneven loading will occur among two of the three lower body joints, but not evenly distributed among all three. It is also known that stronger humans produce a significantly higher amount of net work with increasing force demands as compared to weaker counterparts. Weaker individuals also give a higher negative to positive work ratio (McBride & Nimphius, 2020). Particularly, weaker individuals produce a significantly larger amount of negative work in the knees at the greatest force demands compared to strong individuals.

Physiologically, males and females have vastly different muscle characteristics. Typically, males are stronger and have larger type II muscle fiber areas in the vastus lateralis compared to females. Males also had a larger proportion of type II fibers when compared to females, and these fibers composed 20% more space than type I fibers in the vastus lateralis. Females had no significant difference in fiber type or distribution in the same muscle (Miller et al., 1993). Despite no significant difference in motor unit characteristics, males had overall greater strength measures due to larger muscle fibers. While observing runners, male participants were found to have a higher magnitude of forces in the hamstrings gastrocnemius, and soleus muscles (Vannatta et al., 2020). These differences in muscle physiology have been shown to affect energy algorithms between the sexes. During flat surface walking, females produce greater hip flexion pre-foot contact and greater knee joint power absorption upon landing compared to males (Kerrigan et al., 1998). Despite greater knee joint power, the literature has also indicated a significantly lower resultant force in the knee at landing (Obrębska et al., 2020). Thus, females walk with a more knee-dominant model than males and have different joint work distribution. During a controlled descent, such as on stairs, females were cited to have a lower peak knee extension moment and power and a lower distance between the ground and toe, changing the ankle kinetics during stabilization, resulting in a COM more anterior when compared to males.

Their overall stair descent strategy was significantly different from the males that reduced the demand for lower extremity muscle activation (Hong & Shin, 2015). With increasing eccentric demands such as jumping with a weighted vest, females also showed an overall greater lower extremity work through the knees and ankles despite lower landing heights and peak vertical GRF compared to males (Harry et al., 2019). These results indicate a unique accommodation strategy among sexes, with females utilizing a much more knee dominant model.

The premise of sex-based differences in sub-system joint work is a topic that is well researched. During the pre-swing phase of gait, for example, females are found to have greater peak knee power absorption and higher absolute values of external moments (Kerrigan et al., 1998; Obrębska et al., 2020). The landing phase of gait also showed greater knee adduction, hip adduction, and hip internal rotation (Kerrigan et al., 1998; Sakaguchi et al., 2014) In a semi-squat landing position, females were found to convert kinetic energy into negative ankle work, whereas males were found to convert it to heat loss due to friction (Wan et al., 2017). In a study with increasing eccentric loads, males were found to have had no significant difference in work produced in the hip, knee, and ankle throughout. Females, however, had significantly greater work done in the knee than the hip and ankle at drop jumps from 60 and 75 cm (DJ60 and DJ75), and significantly greater work done in the ankle than the hip and knee in a countermovement jump, a drop jump from 15 cm, and a drop jump from 30 cm. Additionally, females had a significantly higher negative to positive work ratio compared to males at the DJ60 and DJ75. With such strong differences in even the most basic of motions such as walking, one would expect to see nuanced energy algorithms amongst sexes. Previous research demonstrated that male participants produced the largest amount of positive work in the ankle during the countermovement jump and lowest three drop jumps, while the hip and knee produced the largest amount of positive work in the highest two drop jumps. Although female participants produced the most work in the ankles during the countermovement jumps and lowest three drop jumps, they also produced a statistically significant amount of negative work in the knee during the highest two drop jumps, indicating that energy was dispersed in the knees (McBride & Nimphius, 2020). As with walking on even ground, the countermovement and lowest three drop jumps utilized the ankle joint as the primary positive work producer. With rising eccentric demand, however, females and weaker participants produced more negative work than positive work, primarily in the knee. With a lower capacity to produce positive work while fatigued, one would expect to see the results of this study supported with larger margins of difference between individuals.

For the purposes of our study, we define muscular fatigue as the phenomenon in which maximal force production is decreased in response to repeated contractile activity. With this prolonged muscular contraction, adaptations in the central and peripheral neuromuscular centers induce muscular fatigue, reducing muscular efficiency, changing muscle fiber physiology, and altering central nervous system behavior (Enoka & Duchateau, 2008; Gordon et al., 2004; Laubacher et al., 2017). Among these nervous system adaptations are changes in firing rate. Spatially distributed sequential stimulation, where several neural firings activate different subcomponents of a target muscle, has been shown to produce higher power outputs and fatigue resistance than a single electrode stimulation, or a continuous signal that activates a target muscle (Laubacher et al., 2017). When a muscle begins to fatigue, the nervous system increases firing rate to the muscle to try to increase its power output. Muscular efficiency, or how much energy consumed by a muscle fiber is converted into useful mechanical work, is primarily affected by how efficiently the body recruits motor units to create muscular contractions (Enoka

& Duchateau, 2008). According to Henneman's size principle, motor units are recruited from smallest to largest, with the amount of energy needed to complete the contraction proportional to the size of motor units being recruited. During fatigued exercise, a motion that would typically only need small motor unit recruitment requires larger units to be recruited as the smaller units are exhausted (Gordon et al., 2004). With larger units recruited to complete the same action, more energy is used to produce the same contraction, which both reduces muscular efficiency and exhausts the most easily accessible energy systems, ATP Hydrolysis, and the Phospho-Creatine System, more rapidly. As the two quickest energy systems within the cell, the absence of ATP creates an energy deficit within the neuromuscular system, and contraction processes can no longer occur as quickly as they began (Wan et al., 2017). These changes in motor unit recruitment are expected to cause unique energy algorithms in the lower body as muscle activation changes.

Fatigue can also be induced by the physiological reaction to a tetanic contraction, or a constant, prolonged neurological signal from the central nervous system. Within the muscle fiber, continuous electrical signals prevent the return of potassium to the intracellular space, decreasing the interior voltage of the cell and raising the action potential required for a muscle to contract. This constant electrical signal also lowers the excitability of the neuromuscular junction, which decreases motor unit firing rate (Enoka & Duchateau, 2008). These easily accessible energy systems are also responsible for primary muscle contraction and provide the initial energy essential to muscular contraction. When depleted, the products of these exergonic reactions are left free floating in the extracellular space of the cell. The central nervous system detects higher levels of these products and slows the motor unit firing rate to initiate the cardio-respiratory recovery response and reduce the total muscle fiber contractions within the muscle.

As muscle fiber contractions are reduced during fatigue, total muscle force decreases. With increasing force demands and decreasing force production, one would expect an adaptation to energy dispersion, producing greater negative work in the knees and ankles. One of the applications of these neurological and physiological changes is in landing performance. Essential to takeoff and landing while jumping, balance and balance recovery have unique joint work demands. Two essential joints to maintaining and recovering balance are the ankle and knee joints, as previously stated they provide transverse and sagittal stability respectively to the lower body (Nagano et al., 2015). In controlled environments relating fatigue and landing, subjects showed a decrease in GRF and an increase in knee joint impulse, indicating that more energy was expended in the knee than in non-fatigued trials (Madigan & Pidcoe, 2003). These results are consistent with findings that fatigue has a significant effect on landing outcomes in the ankle joint, including work production (Jayalath et al., 2018). Takeoff during jumping is also significantly affected by fatigue. A 20% decrease in single leg hop performance from 29 cm was reported post fatigue protocol. Additionally, knee and ankle power showed a statistically significant decrease post fatigue (Augustsson et al., 2006). With takeoff and landing principles affected by fatigue and so much pivoting from the performance of ankle and knee joints, one would expect to see an increasingly negative work model with increasing eccentric load post fatigue.

Fatigue based sex differences have both physiological and work production consequences. As females do not typically experience the blood flow occlusion to muscles that males do, females are able to perform a task for longer prior to muscle failure, and at the rectus femoris specifically they produce a higher relative activation at failure. When blood flow occlusion is induced, the time to failure in males compared to females is not significantly different (Clark et al., 2005). During prolonged contraction, one study found that electromyography (EMG) signals increased at a slower rate in females compared to males during prolonged contractions; however, another study found no significant difference in EMG activation (Hunter et al., 2004). More research is needed in this area of EMG activation, but these results show the possibility that females can recruit smaller motor units for longer periods of time, increasing their endurance. In application, the literature showed that females were able to perform both intermittent and isometric contractions for longer periods of time before exhaustion compared to males. Overall, many studies found that females were more suited to recover from fatigue more quickly, as separate studies cite that although they cannot sustain maximal contractions for as long, they showed a smaller decrease in maximal voluntary contraction signals and recovered faster (Enoka & Duchateau, 2008; Fulco et al., 1999). With such different responses to fatigue among the sexes, one would expect to see a shift from a knee dominant work loop to a hip-based work loop among females post fatigue as they are able to produce more positive work.

Understanding how joint energy is dispersed among the body is essential for the understanding of organismal locomotion. Expressed as positive and negative work, these energy patterns can be easily altered with changes in force demands, levels of fatigue, strength discrepancies, or sex differences (Harry et al., 2019; Hong & Shin, 2015; McBride & Nimphius, 2020). Using PCA analysis to create models of movement, researchers have begun to discover systems that maximize efficiency in animals and humans alike for discrete movements. This standardization has been difficult to achieve when considering sex differences because of their distinct muscular, kinematic, and kinetic characteristics. Literature indicates that females typically operate under a more knee dominant model, while males typically operate under a more hip dominant model (Clark et al., 2003; Harry et al., 2019; Hong & Shin, 2015; McBride & Nimphius, 2020). Another factor that changes joint work is fatigue, however the effect fatigue has on the distribution of work among the joints among different strengths and sexes is not well understood. The work of McBride and Nimphius characterized these trends without fatigue and found that under the most demanding force conditions, females and weaker individuals produced a significantly higher negative work in the knee and created a negative work loop (McBride & Nimphius, 2020). Furthermore, females jumping with a weighted vest exhibited greater lower extremity work in the knees and ankles even with lower landing heights and peak vertical GRF (Harry et al., 2019). Gait analyses conducted by sex show similar results, with higher knee joint power absorption in females over males (Kerrigan et al., 1998). Despite such knowledge regarding changes via force demands, strength discrepancies, and sex, very little is known about how a lower-limb energy algorithm responds to increasing force demands under fatigued conditions. The purpose of the current study was to evaluate the effect of fatigue on sub-system joint energy algorithms in the hip, knee, and ankle among healthy adults, while taking into consideration differences in strength and sex. We hypothesized that the pre-fatigue conditions will show males and high strength individuals will produce a hip-dominant work model, and females and low strength individuals will produce a knee-dominant work model. We also hypothesized that post-fatigue conditions will augment the results of the pre-fatigue condition.

Methods

Participants

Twenty subjects, 10 males and 10 females aged 18 to 45 years old with no explicit previous jump training volunteered for the current study ($age = 24.25 \pm 4.6\ years,\ height = 172.74 \pm 10.25\ cm,\ weight = 81.71 \pm 21.03\ kg$). Participants were required to have no previous lower body musculoskeletal injuries. Written voluntary consent was given from each subject prior to their participation. The study was approved prior to the investigation by the university's Institutional Review Board. Subjects were recruited from Appalachian State University and the surrounding community of Boone, North Carolina via direct contact, email, and flyer. Leg length, knee width, and ankle width were taken in addition to subject height and weight.

Procedure

Each participant completed two days of data collection approximately one week apart and were randomized to conduct the control or experimental day first. During the control data collection day, subjects completed two trials of the following jumps: a bilateral countermovement jump (CMJ), a drop jump from 15 cm (DJ15), a drop jump from 30 cm (DJ30), a drop jump from 45 cm (DJ45), a drop jump from 60 cm (DJ60), and a drop jump from 75 cm (DJ75) to create different levels of eccentric load. After completion of the first session, subjects sat in a chair for 10 minutes while exerting minimal force from their legs. Participants then repeated the above procedure. Post-jump trials, males ($n = 10$) and females ($n = 10$) performed a 1-RM back squat. Squat weights were normalized by body weight

($relative\ squat\ mean = 1.469 \pm 0.354$), and participants were placed in high strength (HS) and low strength (LS) groupings for statistical comparisons ($HS\ cut-off > 1.431$). During the experimental session, participants completed the same testing procedure but replaced the mandated rest time with six 1-minute duration Wingate tests with resistance set at 30% body weight. 3-minutes of rest were given between each test. During the first and last test, maximum revolutions per minute (RPM) differential [1] , minimum RPM [2] , T1 differential [3] , and T6 differential[4] were recorded.

Data Collection

Trials were performed on two force plates (1,200x600 mm, AMTI, Watertown, MA), one per foot, at a sampling rate of 1000 Hz. Three-dimensional motion analysis was performed by using a 3D infrared 8-camera VICON motion analysis system (Oxford Metrics, Oxford, UK) at a sampling rate of 200 Hz. Participants were fitted with sixteen retro-reflective markers that were placed in specific anatomical locations for motion capture. Locations of eight retro-reflective markers on each side of the lower extremities include the anterior and posterior hip, mid-thigh, lateral epicondyle of femur, mid-tibia, lateral malleolus, insertion point of the Achilles tendon into the calcaneus, and the fifth metatarsal. A static calibration trial was taken with each participant prior to any jump trials. Participants were given instructions to stand upright on a force plate and given the choice to hold their arms crossed over their chest and with their hands on their shoulders or with elbow out and hands placed at the bottom of the rib cage. Data was collected via Vicon Nexus software (Version 2.7.1, Oxford, UK). Nexus software was utilized

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[1] Max RPM test 1 minus Max RPM test 6
[2] Min RPM test 1 minus Min RPM test 6
[3] Max RPM test 1 minus Min RPM test 1
[4] Max RPM test 6 minus Min RPM test 6

for all initial data analysis to find marker trajectories and link force plate data to motion data. All force plate data was passed through a zero-lag fourth-order, 11Hz, lower-pass, Butterworth filter. Inverse dynamics were used in the sagittal plane to calculate joint acceleration, displacement, velocity, and moment. Secondary data analysis was conducted using a customized LabView program (Version 2012, National Instruments, Austin, TX). Work at each joint was calculated as the integral of moment with respect to angular displacement and normalized to the body mass of each participant. Net work was calculated as the sum of the positive and negative work values.

Statistical Analysis

Groups were generated by assigning variables to session type (pre- or post-fatigue), sex (male or female), and strength type (LS or HS) and dividing participants by each type. Means and standard deviations were calculated for descriptive statistics of all participants and divided by sex and strength type. Strength groupings were divided into the 10 participants with the lowest squat 1RM/BM ratio ($LS < 1.431$) and the 10 participants with the highest squat 1RM/BM ratio ($HS \geq 1.431$). A general linear model two-way analysis of variance was utilized to examine the effects of sex (M, W) and jump type (CMJ, DJ15, DJ30, DJ45, DJ60, DJ75) within the pre-fatigue session on negative, positive, and net work of the hip, knee, and ankle. The same analysis was conducted for both the post-fatigue session and for strength level (LS, HS) examinations of the same variables. A general linear factorial analysis of variance was utilized to examine the effects of sex, jump type, and session type. The same analysis was conducted to examine the effects of strength, jump type, and session type. If a significant main effect ($p < 0.05$) and F-statistic ($F \geq 1$) were found, a Tukey post-hoc test was conducted to determine between group differences. If a significant main effect ($p < 0.05$) but not a significant F-statistic ($F \leq 1$) was found, a Bonferroni post-hoc test was conducted to determine between group differences. All analyses were performed using RStudio (Version 4.2.2, Boston, MA) and JASP (Version 0.17.1, Amsterdam, NL).

Results

Participants

Table 1 gives the descriptive statistics for the testing population as a whole, by sex, and by strength. Fatigue was measured by the average RPM differential in the first test ($mean = 32 \pm 8\ RPM$) versus the sixth test ($mean = 38 \pm 13\ RPM$). On average, participants had both higher maximum RPMs ($mean = 2.50\ RPM \pm 12.30\ RPM$) and lower minimum RPMs ($mean = 1.50 \pm 23.12$) in the sixth test than the first. The mean sixth test differential (T6 differential) was higher than the mean T1 differential but had a higher variance ($mean\ T6 = 29.750\ RPM \pm 28.26\ RPM$, $meant\ T1 = 25.75\ RPM \pm 12.06\ RPM$).

Table 1

Descriptive Statistics

	Age (Years)	Height (cm)	Weight (kg)	Relative 1RM (1RM/BW)
All	24 ± 4	173 ± 10	81.7 ± 21.0	1.47 ± 0.35
M	24 ± 3	181 ± 5	92.9 ± 19.3	1.55 ± 0.26
W	25 ± 6	164 ± 6*	70.5 ± 16.8*	1.39 ± 0.43
HS	24 ± 5	175 ± 10	83.0 ± 19.4	1.76 ± 0.23
LS	25 ± 4	170 ± 10	80.4 ± 23.5	1.17 ± 0.13*

Note. Table 1 gives age, height, weight, and relative 1RM for the population as a whole, by sex, and by strength.

Net Work

Trials that contained data with motion capture errors were excluded from the data. All reported significant differences have a p-value less than 0.05. A summary of the number of observations per jump is given in Table 2. In our entire subject pool, significant differences were found in the Pre-fatigue condition for the ankle, knee, and hip net work. Net ankle work ($F(5, 72) = 11.337$, $p < 0.001$) was significantly lower in the CMJ than all jump types and in the DJ15 than DJ75. In contrast, net knee work ($F(5, 72) = 10.264$, $p < 0.001$) was significantly higher in the CMJ than all but the DJ15 ($p < 0.001$), and the DJ15 was significantly higher than the DJ75. Net hip work had statistically significant differences between the DJ15 with the DJ45, DJ60, and DJ75 jumps ($F(5, 72) = 5.223$, $p < 0.001$). In the post fatigue session, significant differences were also present in each joint. Net ankle work ($F(5, 49) = 3.749$, $p = 0.006$) was significantly higher in the CMJ than the DJ60 and DJ75. Knee net work ($F(5, 49) = 3.031$, $p = 0.018$) was also significantly higher in the CMJ than in the DJ75. The DJ15 produced a higher net hip work ($F(5, 49) = 3.707$, $p = 0.006$) than the DJ75. No significant differences were present among the population as a whole, considering males and females separately, and LS and HS separately from pre- to post-fatigue ($p > 0.05$).

Table 2

Observations

		CMJ	DJ15	DJ30	DJ45	DJ60	DJ75
Pre	Whole	12	17	15	15	11	8
	M	6	10	7	9	5	4
	W	6	7	8	6	6	4
	HS	5	9	7	9	6	5
	LS	7	8	8	6	5	3
Post	Whole	9	9	10	9	11	7
	M	4	3	5	4	5	3
	W	5	6	5	5	6	4
	HS	3	4	5	5	5	4
	LS	6	5	5	4	6	3

Note. Table 2 contains the number of observations recorded for each jump type in the whole population, grouped by sexes, and grouped by strength.

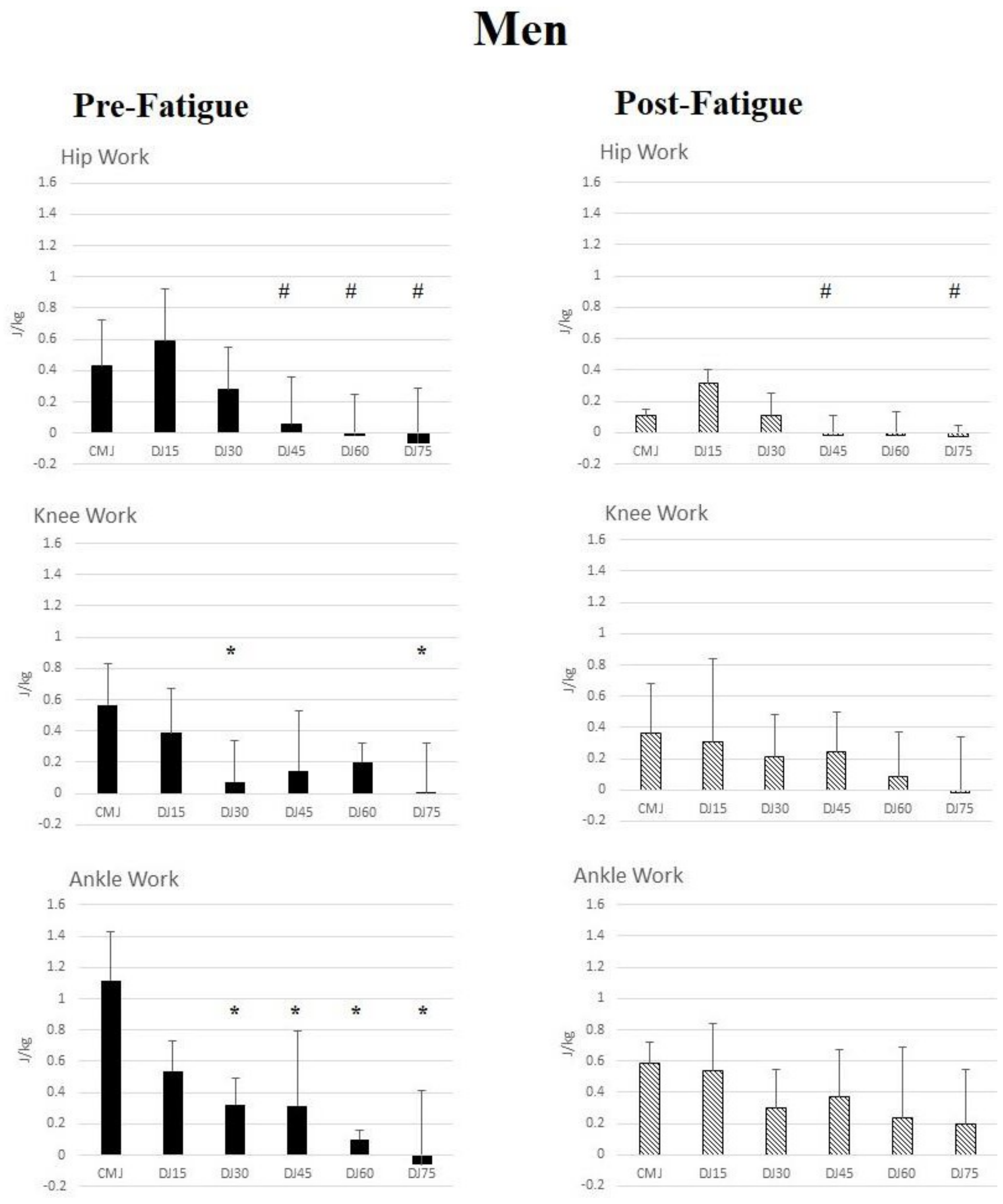
Net Work by Sex

The male subject pool had significant differences in net ankle ($F(5, 35) = 9.305$, $p < 0.001$), knee ($F(5, 35) = 3.138$, $p = 0.019$), and hip ($F(5, 35) = 5.531$, $p < 0.001$) work in the Pre-fatigue session (Figure 1). The CMJ had significantly higher net ankle work than the DJ30, DJ45, DJ60, and DJ75, and had significantly higher knee work than the DJ30 and DJ75. Net hip work was not significantly higher in the CMJ than any jumps but was higher in the DJ15 than in the DJ45, DJ60, and DJ75. Post fatigue, only net hip work was significantly different among jump types ($F(5, 18) = 3.905$, $p = 0.014$). The DJ15 was significantly higher than DJ45 and DJ75 (Figure 1).

The female subjects showed significant differences in only the net ankle ($F(5, 31) = 3.329$, $p = 0.016$) and the net knee ($F(5, 31) = 12.138$, $p < 0.001$) work Pre-fatigue (Figure 2). In the ankle, the CMJ produced a higher net work than the DJ60 and DJ75. In the knee, the CMJ produced a higher net work than all other jump types, and the DJ15 produced a higher net work than the DJ60 an DJ75. Post fatigue, females had significantly different net work in the ankle ($F(5, 25) = 3.120$, $p = 0.023$), the knee ($F(5, 25) = 4.485$, $p = 0.005$), and the hip ($F(5, 25) = 3.566$, $p = 0.014$). The CMJ produced significantly higher net work in both the knee and ankle than the DJ75, and the DJ15 produced significantly higher net knee work than the DJ75. Net hip work was significantly higher in the DJ15 than the DJ75 (Figure 2). No significant differences were observed between males and females in pre- or post-fatigue for net work, negative or positive hip work, negative or positive knee work, and negative or positive ankle work.

Figure 1

Pre- and Post-Fatigue Net Work by Joint for Men

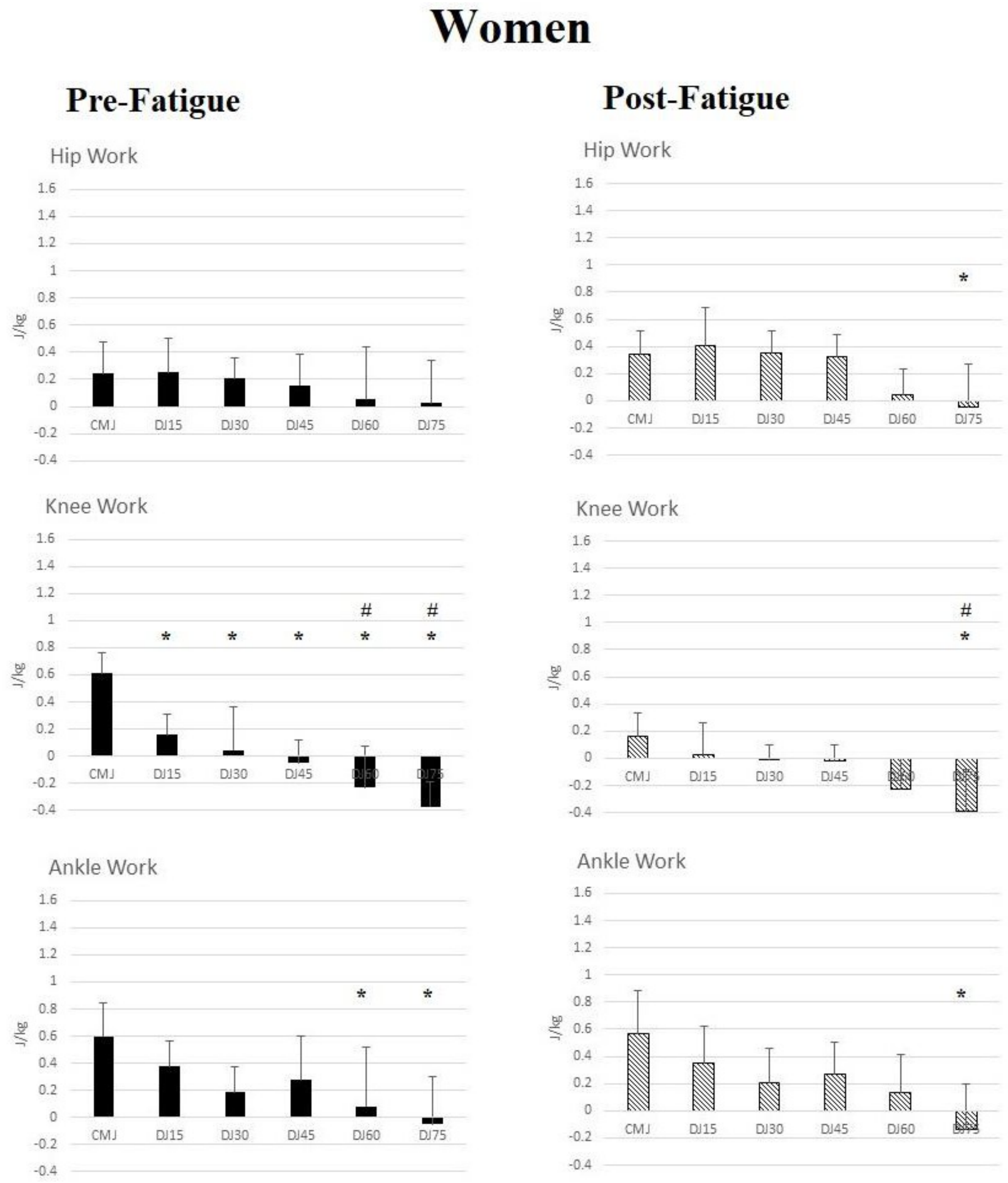


* indicates a significant difference from the CMJ ($p < 0.05$)

# indicates a significant difference from the DJ15 ($p < 0.05$)

Figure 2

Pre- and Post-Fatigue Net Work by Joint for Women



* indicates a significant difference from the CMJ ($p < 0.05$)

\# indicates a significant difference from the DJ15 ($p < 0.05$)

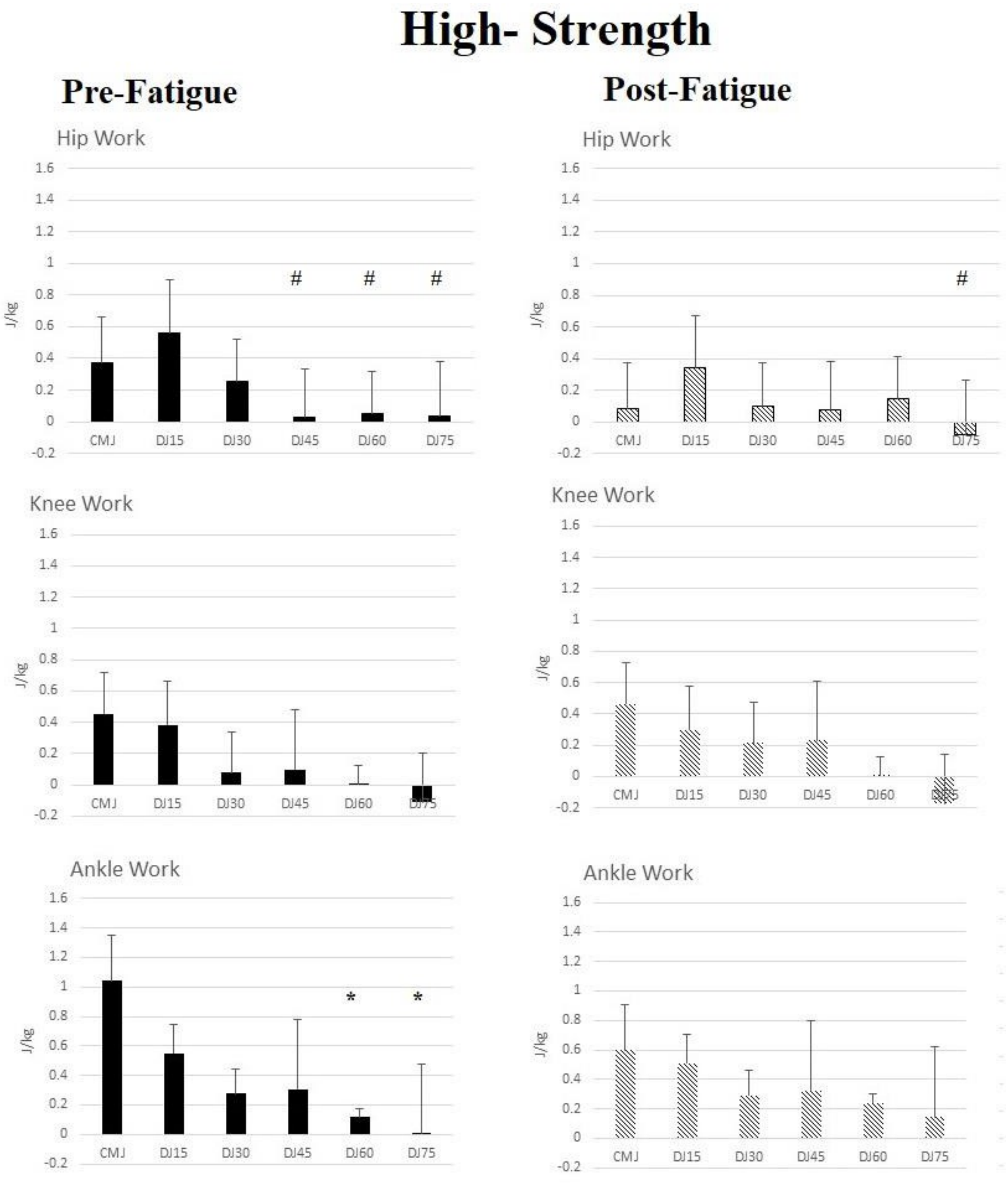
Net Work by Strength Level

High strength (HS) subjects had fewer significant differences in two joints of the Pre-fatigue session and one joint of the post fatigue session. Pre-fatigue, net ankle work ($F(5, 35) = 6.618$, $p < 0.001$) was significantly higher in the CMJ than in the DJ60 and DJ75. Net hip work ($F(5, 35) = 4.096$, $p = 0.005$) was significantly higher in the DJ15 compared to the DJ45, DJ60, and DJ75. Only net hip work was significantly different in the HS post fatigue trial ($F(5, 20) = 3.041$, $p = 0.034$), with DJ15 significantly higher than DJ75 (Figure 3).

Subjects categorized as low strength (LS) had significant differences in both ankle and knee net work during the pre and post fatigue sessions. Pre-fatigue, CMJ was significantly higher than the DJ30, DJ60, and DJ75 in net ankle work ($F(5, 31) = 5.174$, $p = 0.001$). CMJ was also significantly higher than all other jumps, and DJ15 was significantly higher than the DJ75 in net knee work ($F(5, 31) = 11.506$, $p < 0.001$). Net hip work was not significantly different in the Pre-fatigue session. Post fatigue, the CMJ was significantly higher than the DJ75 in both net ankle work ($F(5, 23) = 3.069$, $p = 0.029$) and net knee work ($F(5, 23) = 2.909$, $p = 0.035$). No significant differences were observed between HS and LS groups in pre- or post-fatigue for net work, negative or positive hip work, negative or positive knee work, and negative or positive ankle work.

Table 3

Pre- and Post-Fatigue Net Work by Joint for High-Strength

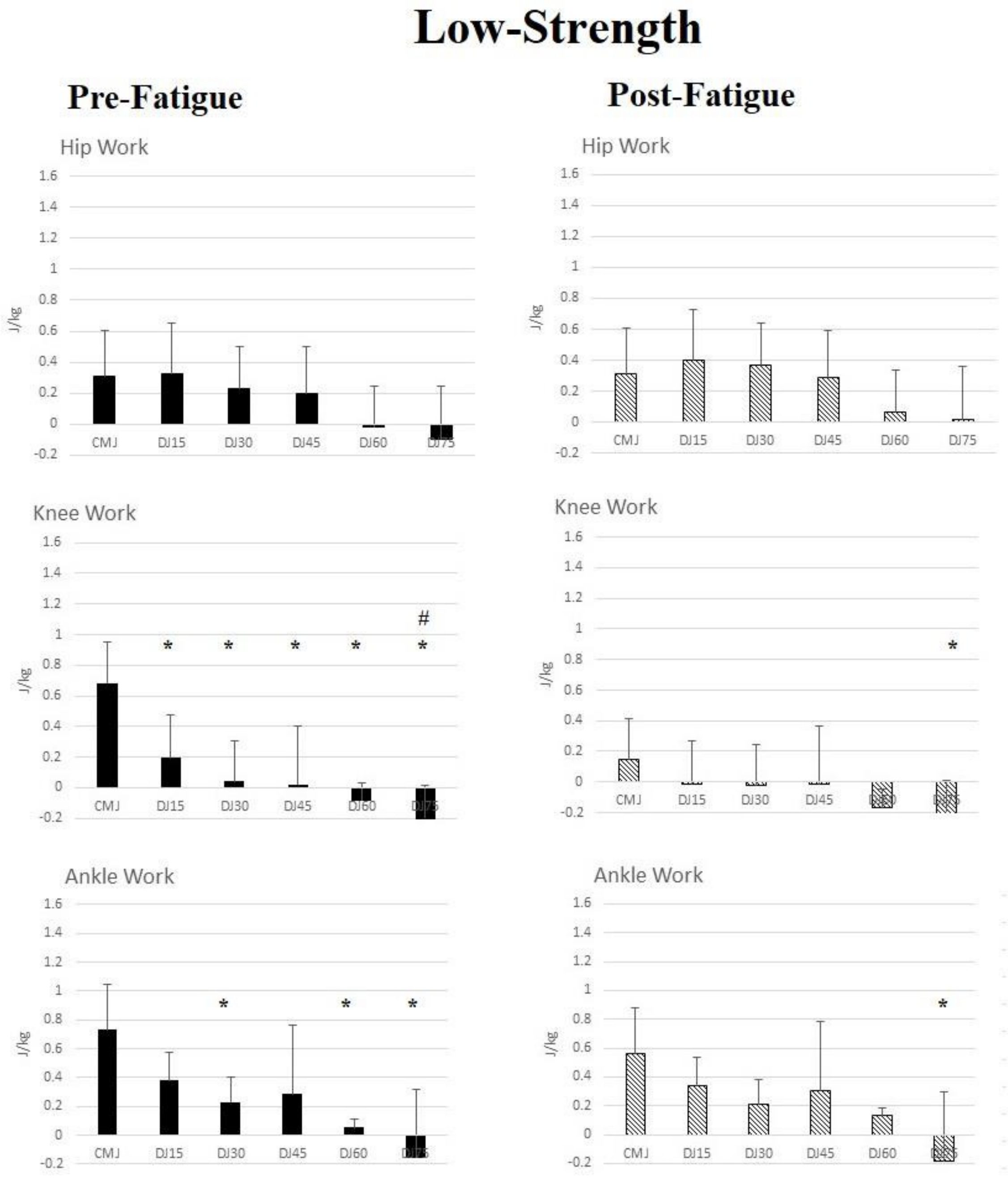


* indicates a significant difference from the CMJ ($p < 0.05$)

# indicates a significant difference from the DJ15 ($p < 0.05$)

Figure 4

Pre- and Post-Fatigue Net Work by Joint for Low-Strength



* indicates a significant difference from the CMJ ($p < 0.05$)

\# indicates a significant difference from the DJ15 ($p < 0.05$)

Positive and Negative Work by Joint

Means and standard deviations for the entire subject pool were calculated for the average amount of positive and negative work between both legs (Table 3). Positive work of the knee, ankle, and hips were not significantly different between jump types in neither the pre nor post fatigue conditions. In the Pre-fatigue session, DJ75 had significantly higher negative hip work ($F(5{,}72) = 3.709$, $p = 0.005$) than both the CMJ and DJ15. Negative knee ($F(5{,}73) = 10.804$, $p = 0.001$) and ankle work ($F(5{,}37) = 4.479$, $p = 0.001$) were also significantly different in the Pre-fatigue trial, with CMJ producing significantly less negative work than all other jumps in both joints. In the post fatigue session, significant differences were only found in the negative knee ($F(5{,}49) = 5.398$, $p = 0.001$) and negative ankle work ($F(5{,}49) = 5.512$, $p < 0.001$) produced. In the knee, DJ75 produced a significantly larger amount of negative work than the CMJ , DJ15, and DJ30. Negative ankle work was significantly lower in the CMJ than in the DJ30, DJ45, DJ60, and DJ75. No significant differences were found in jumps from pre to post fatigue, but variability in the post fatigue session was higher than in the Pre-fatigue for all positive joint work (Hip Post- $F(5, 72) = 0.648$, Knee- $F(5, 72) = 0.622$, Ankle- $F(5{,}72) = 0.203$) (Table 2).

Positive and Negative Joint Work by Sex

Considering only our male participants, Pre-fatigue joint work differences existed only in the negative knee ($F(5, 35) = 3.066$, $p = 0.021$) and ankle work ($F(5, 35) = 3.843$, $p = 0.007$). Negative knee work was significantly lower in the CMJ than in the DJ30, DJ45, DJ60, and DJ75. Negative ankle work CMJ was only significantly lower than DJ60 and DJ75. Post fatigue among males only showed a significant difference among jump types in negative

Table 3

Positive and Negative Work by Joint

	Pre		Post	
	Pos Hip (J/kg)	Neg Hip (J/kg)	Pos Hip (J/kg)	Neg Hip (J/kg)
CMJ	0.69 ± 0.31	0.36 ± 0.19	0.49 ± 0.25	0.25 ± 0.15
DJ15	0.81 ± 0.35	0.36 ± 0.12	0.76 ± 0.39	0.38 ± 0.24
DJ30	0.75 ± 0.34	0.51 ± 0.22	0.63 ± 0.35	0.40 ± 0.29
DJ45	0.63 ± 0.44	0.53 ± 0.30	0.61 ± 0.39	0.44 ± 0.24
DJ60	0.65 ± 0.54	0.63 ± 0.32	0.58 ± 0.34	0.47 ± 0.31
DJ75	0.73 ± 0.54	0.75 ± 0.31**	0.72 ± 0.44	0.76 ± 0.44*

	Pre		Post	
	Pos Knee (J/kg)	Neg Knee (J/kg)	Pos Knee (J/kg)	Neg Knee (J/kg)
CMJ	0.80 ± 0.27	0.36 ± 0.19	0.55 ± 0.40	0.30 ± 0.18
DJ15	0.77 ± 0.23	0.36 ± 0.20	0.60 ± 0.39	0.47 ± 0.09
DJ30	0.73 ± 0.51	0.51 ± 0.22*	0.66 ± 0.38	0.56 ± 0.31
DJ45	0.69 ± 0.45	0.53 ± 0.30*	0.81 ± 0.31	0.67 ± 0.33
DJ60	0.76 ± 0.35	0.63 ± 0.32*	0.65 ± 0.44	0.73 ± 0.42
DJ75	0.75 ± 0.43	0.75 ± 0.37*	0.83 ± 0.59	1.06 ± 0.43***

	Pre		Post	
	Pos Ankle (J/kg)	Neg Ankle (J/kg)	Pos Ankle (J/kg)	Neg Ankle (J/kg)
CMJ	0.98 ± 0.43	0.12 ± 0.12	0.67 ± 0.28	0.10 ± 0.05
DJ15	0.84 ± 0.21	0.37 ± 0.18*	0.74 ± 0.31	0.32 ± 0.19
DJ30	0.75 ± 0.30	0.50 ± 0.28*	0.77 ± 0.37	0.52 ± 0.26*
DJ45	0.77 ± 0.44	0.47 ± 0.31*	0.80 ± 0.50	0.48 ± 0.34*
DJ60	0.65 ± 0.49	0.56 ± 0.43*	0.76 ± 0.44	0.58 ± 0.31*
DJ75	0.57 ± 0.48	0.62 ± 0.37*	0.64 ± 0.40	0.64 ± 0.23*

* represents a significant difference from the work in the CMJ ($p < 0.05$)

** represents a significant difference from the work in both the CMJ and the DJ15 ($p < 0.05$)

*** represents a significant difference from the work in the CMJ, DJ15, and DJ30 ($p < 0.05$)

Table 4

Positive and Negative Joint Work by Sex

		Pre		Post	
		Pos Hip (J/kg)	Neg Hip (J/kg)	Pos Hip (J/kg)	Neg Hip (J/kg)
CMJ	M	0.83 ± 0.26	0.40 ± 0.24	0.36 ± 0.27	0.25 ± 0.24 W
		0.56 ± 0.32	0.31 ± 0.14	0.59 ± 0.21	0.25 ± 0.06
DJ15	M	0.92 ± 0.29	0.33 ± 0.19	0.72 ± 0.34	0.40 ± 0.26
	W	0.65 ± 0.39	0.40 ± 0.22	0.78 ± 0.44	0.38 ± 0.25
DJ30	M	0.77 ± 0.41	0.50 ± 0.23	0.41 ± 0.30	0.29 ± 0.25
	W	0.73 ± 0.28	0.52 ± 0.22	0.86 ± 0.23	0.50 ± 0.33
DJ45	M	0.56 ± 0.48	0.51 ± 0.33	0.26 ± 0.27	0.28 ± 0.27
	W	0.73 ± 0.28	0.57 ± 0.28	0.89 ± 0.18	0.57 ± 0.12
DJ60	M	0.46 ± 0.48	0.48 ± 0.31	0.48 ± 0.26	0.30 ± 0.16
	W	0.80 ± 0.58	0.75 ± 0.29	0.66 ± 0.40	0.61 ± 0.36
DJ75	M	0.61 ± 0.51	0.67 ± 0.41	0.64 ± 0.51	0.67 ± 0.50
	W	0.85 ± 0.63	**0.83 ± 0.36***	0.78 ± 0.45	0.83 ± 0.46
		Pre		Post	
		Pos Knee (J/kg)	Neg Knee (J/kg)	Pos Knee (J/kg)	Neg Knee (J/kg)
CMJ	M	0.74 ± 0.29	0.18 ± 0.10	0.67 ± 0.56	0.30 ± 0.25
	W	0.86 ± 0.25	0.25 ± 0.14	0.45 ± 0.25	0.29 ± 0.14
DJ15	M	0.86 ± 0.23	0.47 ± 0.26	0.75 ± 0.57	0.45 ± 0.07
	W	0.64 ± 0.15	0.48 ± 0.13	0.51 ± 0.30	0.45 ± 1.07
DJ30	M	0.66 ± 0.22	0.59 ± 0.37	0.80 ± 0.46	0.59 ± 0.43
	W	0.79 ± 0.40	**0.75 ± 0.15***	0.53 ± 0.26	0.54 ± 0.19
DJ45	M	0.73 ± 0.59	0.58 ± 0.43	0.91 ± 0.38	0.67 ± 0.47
	W	0.64 ± 0.15	**0.69 ± 0.15***	0.72 ± 0.26	0.70 ± 0.23
DJ60	M	0.95 ± 0.09	**0.75 ± 0.20***	0.85 ± 0.52	0.76 ± 0.44
	W	0.59 ± 0.41	**0.82 ± 0.18***	0.48 ± 0.31	0.71 ± 0.44
DJ75	M	0.87 ± 0.46	**0.86 ± 0.32***	1.26 ± 0.53	1.28 ± 0.30
	W	0.62 ± 0.41	**0.99 ± 0.30****	0.51 ± 0.42	0.90 ± 0.48
		Pre		Post	
		Pos Ankle (J/kg)	Neg Ankle (J/kg)	Pos Ankle (J/kg)	Neg Ankle (J/kg)
CMJ	M	1.23 ± 0.35	0.11 ± 0.04	0.69 ± 0.14	0.11 ± 0.04
	W	0.72 ± 0.35	0.12 ± 0.17	0.65 ± 0.38	0.08 ± 0.06
DJ15	M	0.92 ± 0.22	0.39 ± 0.19	1.03 ± 0.29	0.49 ± 0.03
	W	0.72 ± 0.12	0.34 ± 0.20	0.59 ± 0.21	0.24 ± 0.18
DJ30	M	0.86 ± 0.33	0.53 ± 0.40	1.01 ± 0.30	**0.72 ± 0.18***
	W	0.66 ± 0.25	0.47 ± 0.14	0.53 ± 0.26	0.32 ± 0.16
DJ45	M	0.78 ± 0.57	0.47 ± 0.33	1.16 ± 0.48	**0.79 ± 0.24***
	W	0.75 ± 0.17	0.47 ± 0.31	0.51 ± 0.30	0.24 ± 0.16
DJ60	M	0.92 ± 0.52	**0.82 ± 0.48***	1.02 ± 0.40	**0.79 ± 0.21***
	W	0.42 ± 0.34	0.34 ± 0.23	0.55 ± 0.37	0.41 ± 0.27
DJ75	M	0.72 ± 0.59	**0.78 ± 0.37***	1.01 ± 0.16	**0.81 ± 0.21***
	W	0.42 ± 0.35	0.47 ± 0.34	0.37 ± 0.26	**0.51 ± 0.17***

* signifies a significant difference from the CMJ ($p < 0.05$)

** signifies a significant difference from the CMJ and DJ15 ($p < 0.05$)

ankle work ($F(5, 35) = 9{,}394$, $p < 0.001$), with CMJ producing significantly lower negative work than DJ30, DJ45, DJ60, and DJ75 (Table 4). No significant differences in ankle, knee, or hip joint work were found comparing Pre-fatigue to post fatigue, but variability was higher in the post fatigue condition among males in the positive ankle work ($Pos\,Ank\,Pre - F(5, 35) = 1.003$, $Pos\ Ank\ Post - F(5, 35) = 0.868$).

In only female participants, the Pre-fatigue condition only showed significant differences in negative hip ($F(5, 35) = 3.335$, $p = 0.016$) and knee work ($F(5, 35) = 13.018$, $p < 0.001$), in which CMJ negative hip work was significantly lower than the DJ75, and CMJ negative knee work in the CMJ significantly lower than the DJ30, DJ45, DJ60, and DJ75. DJ15 also had significantly lower negative knee work than the DJ60 and DJ75 in the Pre-fatigue session among females. Post fatigue had no significant differences in any of the joint work variables. No statistically significant difference was found for the amount of positive and negative work in the ankle, knee, and hip in any jump type between males and females (Table 3).

Positive and Negative Joint Work by Strength

Groupings were also divided by two strength categories (low strength- LS, and high strength- HS). Pre-fatigue, both negative hip ($F(5, 31) = 3.269$, $p = 0.017$) and knee ($F(5, 31) = 5.709$, $p < 0.001$) work had statistically significant differences among jumps in the LS group (Figure 5). CMJ negative hip work was significantly lower than the DJ75, and CMJ negative knee work was significantly lower than the DJ30, DJ45, DJ60, and DJ75. Post fatigue had no significant differences between jumps. No significant differences from pre to post fatigue were found, but low F values were found for positive hip work ($F(5{,}54) = 0.153$), negative hip work ($F(5{,}54) = 0.447$), and negative ankle work ($F(5{,}54) = 0.261$) when looking at these relationships.

HS participants showed significant differences between jumps in pre and post fatigue conditions. Pre-fatigue, negative knee work ($F(5{,}35) = 4.903$, $p = 0.002$) was significantly higher in the DJ75 than the CMJ and DJ15. In the post fatigue session, both negative knee ($F(5{,}20) = 4.229$, $p = 0.009$) and ankle ($F(5{,}20) = 4.945$, $p = 0.004$) work had significant differences among jumps. Again, no significant differences were found in the high strength group pre to post fatigue, but low F values were found for positive knee work ($F(5, 54) = 0.248$) and negative ankle work ($F(5, 54) = 0.281$) (Table 4).

Discussion

The current study aimed to evaluate sub-system joint work in the ankle, knee, and hip among healthy adults, observe the effect of fatigue on these systems. It also aimed to evaluate if these effects were more prevalent in certain sexes or strength levels. Significant findings of the study include that the only significant joint work differences were in the negative work, more differences between males and females existed than between strength levels, females and weaker individuals shifted to a higher negative knee work model with increasing loads, and the post fatigue condition had higher levels of variance in net, positive, and negative work values.

All work types that were significantly different looking at positive and negative work were negative joint work types. The positive work analyzed in the hip, knee, and ankle was not significantly different in any jump or fatigue condition. In contrast, negative work showed significant differences between jump type in all three joints in both the pre and post fatigue conditions (Table 3). From these results, one can conclude that any net joint work changes

Table 5

Positive and Negative Joint Work by Strength

		Pre		**Post**	
		Pos Hip (J/kg)	Neg Hip (J/kg)	Pos Hip (J/kg)	Neg Hip (J/kg)
CMJ	HS	0.85 ± 0.30	0.48 ± 0.20	0.27 ± 0.25	0.18 ± 0.25
	LS	0.58 ± 0.29	0.27 ± 0.14	0.60 ± 0.20	0.28 ± 0.10
DJ15	HS	0.93 ± 0.35	0.36 ± 0.23	0.85 ± 0.38	0.50 ± 0.30
	LS	0.68 ± 0.32	0.35 ± 0.18	0.69 ± 0.42	0.29 ± 0.14
DJ30	HS	0.75 ± 0.38	0.50 ± 0.24	0.47 ± 0.41	0.37 ± 0.38
	LS	0.75 ± 0.32	0.52 ± 0.22	0.79 ± 0.20	0.42 ± 0.21
DJ45	HS	0.59 ± 0.49	0.56 ± 0.34	0.40 ± 0.39	0.32 ± 0.25
	LS	0.69 ± 0.37	0.49 ± 0.26	0.88 ± 0.20	0.59 ± 0.13
DJ60	HS	0.67 ± 0.65	0.62 ± 0.37	0.60 ± 0.41	0.45 ± 0.43
	LS	0.62 ± 0.44	0.64 ± 0.28	0.56 ± 0.31	0.49 ± 0.22
DJ75	HS	0.75 ± 0.55	0.72 ± 0.37	0.75 ± 0.47	0.83 ± 0.52
	LS	0.70 ± 0.66	**0.80 ± 0.43***	0.69 ± 0.51	0.67 ± 0.40

		Pre		**Post**	
		Pos Hip (J/kg)	Neg Hip (J/kg)	Pos Hip (J/kg)	Neg Hip (J/kg)
CMJ	HS	0.69 ± 0.30	0.24 ± 0.13	0.83 ± 0.55	0.37 ± 0.25
	LS	0.88 ± 0.24	0.19 ± 0.13	0.41 ± 0.25	0.26 ± 0.15
DJ15	HS	0.82 ± 0.27	0.43 ± 0.16	0.80 ± 0.48	0.51 ± 0.13
	LS	0.71 ± 0.17	0.52 ± 0.26	0.42 ± 0.24	0.44 ± 0.03
DJ30	HS	0.67 ± 0.23	0.60 ± 0.26	0.87 ± 0.41	0.66 ± 0.40
	LS	0.78 ± 0.39	**0.74 ± 0.29***	0.45 ± 0.21	0.47 ± 0.20
DJ45	HS	0.68 ± 0.53	0.58 ± 0.36	0.89 ± 0.33	0.66 ± 0.41
	LS	0.71 ± 0.35	**0.68 ± 0.34***	0.71 ± 0.30	**0.72 ± 0.25***
DJ60	HS	0.77 ± 0.38	0.77 ± 0.17	0.99 ± 0.35	0.98 ± 0.38
	LS	0.74 ± 0.36	**0.82 ± 0.22***	0.36 ± 0.25	0.52 ± 0.35
DJ75	HS	0.80 ± 0.43	**0.92 ± 0.30****	1.17 ± 0.47	**1.35 ± 0.28****
	LS	0.65 ± 0.50	**0.95 ± 0.36***	0.37 ± 0.38	0.68 ± 0.22

		Pre		**Post**	
		Pos Hip (J/kg)	Neg Hip (J/kg)	Pos Hip (J/kg)	Neg Hip (J/kg)
CMJ	HS	1.13 ± 0.40	0.09 ± 0.05	0.69 ± 0.18	0.10 ± 0.04
	LS	0.87 ± 0.44	0.14 ± 0.15	0.66 ± 0.34	0.09 ± 0.06
DJ15	HS	0.91 ± 0.25	0.36 ± 0.20	0.98 ± 0.25	0.47 ± 0.04
	LS	0.76 ± 0.11	0.38 ± 0.18	0.55 ± 0.20	0.21 ± 0.18
DJ30	HS	0.72 ± 0.26	0.47 ± 0.33	0.93 ± 0.44	**0.64 ± 0.20***
	LS	0.78 ± 0.34	0.55 ± 0.24	0.61 ± 0.23	0.40 ± 0.29
DJ45	HS	0.77 ± 0.56	0.46 ± 0.30	1.00 ± 0.54	**0.68 ± 0.32***
	LS	0.77 ± 0.21	0.48 ± 0.35	0.54 ± 0.33	0.24 ± 0.19
DJ60	HS	0.64 ± 0.50	0.52 ± 0.46	1.01 ± 0.41	**0.77 ± 0.20***
	LS	0.66 ± 0.53	0.60 ± 0.43	0.56 ± 0.38	0.43 ± 0.30
DJ75	HS	0.69 ± 0.52	0.69 ± 0.38	0.88 ± 0.27	**0.74 ± 0.21***
	LS	0.37 ± 0.41	0.52 ± 0.39	0.32 ± 0.29	0.50 ± 0.21

* represents a significant difference from the work in the CMJ

** represents a significant difference from the work in both the CMJ and the DJ15 ($p < 0.05$)

were the result of changing negative work. Thus, with greater eccentric load, participants did not produce significantly more positive work, but did produce significantly more negative work. These results are in contrast with a study investigating joint work distribution differences between old and young adults, which found that between the two groups, positive work was distributed differently among the joints while negative work distribution remained the same (Waanders et al., 2019). The old adult group, which had reported results of higher lower body weakness and can be compared to the LS group of the current study, utilized a hip dominant positive work model. The young adult group, which can be compared to the HS group of the current study, utilized an ankle dominant model. Even with these differences in positive work distribution, negative work had no such differences. These results remained the same with load changes. The discrepancy in these results could be for several reasons. The first is that, although the study found the younger individuals significantly stronger than the older individuals, older individuals had more confounding variables affecting their movement patterns than our LS group. The second is that the comparison between the old and young groups of the Waanders study is not a perfect one. While it is true that both LS and older adults are weaker than HS and younger adults respectively, the LS group of the current study utilized a predominantly knee dominant model rather than a hip dominant model seen in the older adults. Thus, movement adaptations are likely different. The knee dominant model of the LS group does, however, connect to the knee dominant model of the females in the current study.

Pre-fatigue, females and LS individuals had significantly higher net knee work in the CMJ than in any other jump. In the LS participants, DJ15 net knee work was also significantly higher than the DJ75 (Figures 2 and 3). These results are in conjunction with those of McBride and Nimphius, whose study on non-fatigued joint work distribution saw a shift to higher negative work in the knee at the highest eccentric loads for females and weaker participants (McBride & Nimphius, 2020). This outcome follows reason, as the LS group was comprised of seven of the ten females who participated in the study, and therefore has a higher likelihood to follow their work distribution pattern more closely than that of the males. One can speculate that major result difference between the females and LS groups lies in the DJ60, which had a lower net work in the female group than the LS group and thus was significantly lower than the DJ15 where the LS group was not. This difference could allude to the LS group having an overall higher capacity for net knee work adaptations. None of the above trends significantly carried over to the post fatigue condition, which could indicate that fatigue erases some of the joint work advantages males and stronger participants have over females and weaker participants. When grouped by sexes, males and females did, however, show similarities in their primary joint work solution. Negative knee work was significantly different among jumps for both males ($F(5, 35) = 3.843, p = 0.007$) and females ($F(5, 35) = 13.018, p < 0.001$), with CMJ producing a significantly lower amount of negative work than the DJ60 and DJ75. Where the differences among sexes begin is with the DJ30 and DJ45, in which females had significantly higher negative knee work when compared to the CMJ and the males had no such differences. This indicates that females were shifting to a knee-dominant negative work model sooner than males, supporting the hypothesis that females shift to a knee-dominant model at higher stress and the literature by McBride and Nimphius. Without statistical significance in the post-fatigue data, our hypothesis that this model would appear more strongly post-fatigue was not supported.

Despite the similarity of changing knee work between the sexes, the trends in secondary joint distributions were vastly different. Males appeared to produce a higher overall net work in the hip and ankle that diminished more quickly than females, as pre fatigue net ankle work was significantly lower ($F(5, 35) = 3.066, p = 0.021$) than the CMJ in the DJ30, DJ45, DJ60, and DJ75 in males, compared to only the DJ60 and DJ75 pre fatigue net ankle work in females having a significant difference from the CMJ ($F(5, 31) = 3.329, p = 0.016$). In the hip, males had and pre fatigue net hip work was significantly lower ($F(5, 35) = 5.531, p < 0.001$) than the DJ15 in the DJ45, DJ60, and DJ75, and females had no significant differences (Figure 1). From these differences, one can conclude that at maximum eccentric loads, males and females produce different joint work strategies to solve the same problem. This is not the only motion males and females have been found to utilize different movement strategies. A study by Graci et. al investigating the kinetics and kinematics of the single leg squat found that females had greater hip abduction and knee adduction than males (Graci et al., 2012). A single leg squat mimics that of the eccentric phase of a jumping motion, thus it is possible that the movement solutions would carry over to the jumping patterns tested in the present research.

Differences by strength level were not as prevalent as the differences by sex in the current study. In pre-fatigue conditions, both LS ($F(5, 31) = 5.709, p < 0.001$) and HS ($F(5, 31) = 4.903, p = 0.002$) groups had significant differences in negative knee work. CMJ negative work was significantly lower for both groups at DJ60 and DJ75. This indicates that for both strength groups, joint work strategies changed to increase negative work at the highest eccentric loads. In the LS group, CMJ negative work was also lower than the DJ30 and DJ45. Connecting this finding to our last, the LS group developed a greater negative knee work pattern at a lower eccentric load than the HS group. In the mirroring conditions in McBride and Nimphius, LS participants only exhibited a significant difference between the CMJ and the DJ75. This discrepancy during similar conditions could be due to differences in sample size, mean age, or the presence of only two strength groups in the present research (McBride &

Nimphius, 2020). Negative hip work was only significantly different in the LS group ($F(5, 31) = 3.269$, $p = 0.017$) between the CMJ and DJ75. Post fatigue joint work distributions by sex followed a similar trend to its pre fatigue counterpart. Only negative ankle work in the HS group had a significant difference among jump types, with CMJ significantly lower than the DJ30, DJ45, DJ60, and DJ75. These results could indicate that post fatigue conditions create a larger difference in joint work strategy by increasing overall net work in the system.

Despite having no statistically significant differences in any groupings from pre-fatigue to post, observing patterns in net work changes and the variance among the post-fatigue data shows evidence that fatigue had a significant impact on joint work distribution. The differences outlined in the above paragraphs between our comparisons of interest were greatly diminished with post-fatigue conditions. Compared to the significant differences between the CMJ and all remaining jumps in pre-fatigue net knee work females, post-fatigue females only had a significant difference between the CMJ and the DJ75. The significant differences between the CMJ and DJ30, DJ45, DJ60, and DJ75 in net ankle work that males produced were erased in post-fatigue, as no significant differences were found. Confounding variables such as statistical power could have prevented the statistics from showing a significant difference between the overall net ankle work produced in males from pre- to post-fatigue, but the observations from the graphs in pre to post show a very different shape in bar graphs.

Also supporting fatigue's impact on joint work distribution was the variance found in the post-fatigue data set. Of our entire subject pool, all negative work F statistics, a value that gives the ratio between the variance of group one to the variance of group two, produced an F value lower than 0.5. This indicates that the variance of the post fatigue condition was at least twice that of the variance in the pre-fatigue condition. After excluding outliers, a higher variance indicates that on average, data points have a larger distance from the mean than the pre-fatigue group. Comparing across conditions, one could conclude that a higher variance is indicative of a higher rate of inconsistency in movement strategies in the post-fatigue condition than the pre-fatigue condition. These results align with the work of Singh et. al, who found in their study of force variance in the hand during fatiguing activity that fatigue conditions increase variability of performance. Using the metric of force production, a key component to the work calculation, the study found that force production obtained a higher variability during a fatiguing task than in a non-fatiguing task (Singh et al., 2010). With higher force variability, work variability would also increase. Paired with the washing of significant differences in net work between jump types, the most logical inference is that fatigue caused at least some of these changes.

In our groupings that were evaluated pre to post fatigue, comparisons with the most commonly low F statistic were negative knee work when grouped by sex and negative ankle work when grouped by strength. While negative knee work has many variables that contribute to its production, one component of higher variability in negative knee work by sex is the difference in knee adductor moment (KAM). A study by Sims et. al discovered that knee adduction is one of the significant force producers during jumping and that females produced a higher KAM during normal gait compared to males (Sims et al., 2009). KAM is hypothesized to change due in part by mechanical loading. With too high of a mechanical load, there is a high rate of osteoarthritis development in humans (Souza et al., 2012). A disease caused by repeated force absorption that results in the thinning of cartilage, osteoarthritis has a higher occurrence in females than males (Sims et al., 2009; Souza et al., 2012). Thus, with a higher occurrence and higher KAM between the in females than males, an increasing eccentric load is likely to exaggerate these differences between sexes. When adding another stimulus like fatigue to an already established difference, logic would follow that it would cause further changes. Another source of high variability in post-fatigue conditions were in net ankle work. Ankle movement strategies have also been shown to vary with fatigue. A study in which participants performed a series of isometric contraction tasks pre- and post-fatigue of the plantar-flexor muscles found that fatigued trials produced a higher variability in task performance and a degradation of force (Vuillerme & Boisgontier, 2008). Given that our differences in variability occurred between both strength groups going from pre- to post-fatigue, these results are supported by the study conducted by Vuillerme and Boisgontier. Thus, while fatigue may have not caused a statistically significant change in the mean net work produced, it increased the variability of motion among our subject pool. Therefore, with changes in both variability and net work between jumps, the research of this paper supported the hypothesis that fatigue would change joint work distribution.

A few possible limitations that could have contributed to the lack of statistical significance in our pre- to post-fatigue analyses were too few post-fatigue data points and too many gaps in the initial VICON data due to lost or blocked markers. During data analysis, many work loops were removed from the data due to inconsistent signal or extra noise in the data. Particular care was taken during initial data analyses to normalize the data and remove outliers, however no data cleaning methods are perfect. During data collection, a 16-point marker system was used for the VICON motion capture system. All markers were cleaned and placed in the proper anatomical positions prior to data capture, but during particular motions, specifically at the highest drop jumps and post-fatigue, some markers were obstructed from view. Thus, gap-filling was required to produce model output data. Mathematical approximations created generally good fits to complete the model but could have created more noise within the data set.

With several limitations and some ambiguous results regarding post fatigue conditions, there are many directions for future study. One area of research that could be expanded upon from the current study is the relationship between CMJ and DJ15 work demands and how they compare to higher eccentrically loaded jumps. Net hip work showed significant differences between the DJ15 and the DJ60 or DJ75 jumps, but it is unclear why. Additionally, researchers could investigate the effects of fatigue on single leg jumps compared to countermovement jumps. Finally, the findings regarding negative knee work could help inform future research on the relationship between negative knee work and injury risk.

Conclusion

Through the utilization of increasing eccentric loads and a fatiguing protocol, the current research evaluated joint work patterns in the ankle, knee, and hip in healthy adults for pre- and post-fatigue conditions. These patterns were also evaluated while considering the effects of strength and sex. Overall, the study found significant differences in negative joint work for different jump conditions, joint work distribution strategies between males and females, and the level of variance between the pre and post fatigue sessions. These results have broader implications for the world of injury prevention and endurance-based sporting events that induce high levels of fatigue, such as soccer, baseball, and basketball, as researchers and practitioners alike can use the findings from the present study to inform post-game recovery, play time decisions, and investigate the injury risk associated with changing joint work patterns.

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Appendix A

APPALACHIAN STATE UNIVERSITY

CONSENT FORM

THE EFFECT OF FATIGUE ON SUB-SYSTEM JONT WORK:

INFLUENCE OF SEX, STRENGTH, AND ECCENTRIC LOADING

Researchers: **Human Movement Studies, Graduate Faculty**

Dr. Jeffrey M. McBride, Professor, Human Movement Studies, Beaver College of Health Sciences, Phone: (828)262-6333, Email: mcbridejm@appstate.edu
Ceara Larson, Graduate Student, Exercise Science, Beaver College of Health Sciences, Phone: (309)737-9746, Email: larsonca1@appstate.edu

Researchers Statement:
We are asking you to be in a research study. This form gives you information to help you decide whether or not to be in the study, such as the purpose of study; the procedures, risks, and benefits of the study; how we will protect the information we will collect from you; and how you can contact us with questions about the study or if you feel like you have been harmed by this research. Please read it carefully. You should ask any questions you have about the research and, once they are answered to your satisfaction, you can decide whether or not you want to be in the study. Being in the study is voluntary, and even after you agree to participate, you can change your mind and stop participating at any time without losing any benefits from the University to which you may be entitled.

KEY INFORMATION ABOUT THIS STUDY

The purpose of this study is to observe how the body's joints adapt to increasing physical demands and how they respond to fatigue, especially among individuals of different strength and gender. Consent is being sought out for us to conduct this research and participation is completely voluntary. Participation will include 2 visits lasting approximately two hours in the Neuromuscular and Biomechanics Research Laboratory (LLHS 125). In this study, you will be jumping from several heights ranging from ground level to 75 cm off the ground, performing a 1 rep maximum squat test, and completing up to 6 1-minute Wingate bicycle sprint tests. During data collection, you will learn the technique of a countermovement jump (CMJ), a single leg countermovement jump (SLCMJ), and drop jump (DJ). Special attention will need to be paid to the method of stepping off the box during the drop jump. 3 hours prior to the study, you will need to avoid the use of all drugs and alcohol. By participating in this study, you will be at risk for muscle and tendon strains and sprains, muscle soreness, and moderate fatigue. Biomechanical data and force metrics will be taken from you during these jumps via a 3D motion-capture system (VICON) and a set of force plates (Bertec). The work of this study poses a potential benefit to society and its knowledge of how joint work changes with changing force demands, which could assist in developing exercise programs for fitness and injury prevention as well as assessing an individual's injury risk. There is no potential direct benefit to you as a participant in this study.

PURPOSE OF THE STUDY

Joint work distribution is an essential component to every day movement. Typically expressed in forms of positive, negative, and net work, energy is dispersed or transferred through each joint. The pattern this energy flows through dictates how well humans can walk, run, and jump. However, these distribution patterns are easily changed by changes in force conditions, sex, and fatigue. With increasing demands on the lower body, women and weaker individuals have been found to utilize a significantly higher amount of negative work in the knee, whereas men and stronger individuals have been found to utilize more positive work in the hip. These trends have yet to be investigated in fatigued subjects. The purpose of the current study is to evaluate the effect of fatigue on sub-system joint energy algorithms in the hip, knee, and ankle among healthy adults, while taking into consideration differences in strength and sex.

STUDY PROCEDURES

This study involves 2, two-hour lab visits in the Neuromuscular and Biomechanics Laboratory (LLHS 125) where you will perform several kinds of jumps, participate in Wingate bicycle sprint tests, and perform a 1 rep maximum squat. The lab visits will be approximately one week apart.

Each visit will consist of:

- 4 Countermovement Jumps (CMJ)
- 4 Left Single Leg Countermovement Jumps
- 4 Right Single Leg Countermovement Jumps
- 4 Drop Jumps from 15 cm off the ground
- 4 Drop Jumps from 30 cm off the ground
- 4 Drop Jumps from 45 cm off the ground
- 4 Drop Jumps from 60 cm off the ground
- 4 Drop Jumps from 75 cm off the ground

One of the following will be conducted at each visit:

- A 1 rep maximum back squat test
- Up to 6 1-minute duration Wingate bicycle sprint tests with 30 seconds of rest in between tests

All jumps will be recorded via a fast-motion 3D capture system (VICON) and will be performed on force plates. Other video may be recorded for procedural descriptions. You may refuse to participate at any time during the above procedure.

RISKS, STRESS, AND DISCOMFORTS

This study poses a risk of muscle sprain and strain as well as fatigue. You may feel muscle soreness in the days following data collection or experience mild dehydration. Additionally, you may feel discomfort during our anaerobic sprint testing due to shortness of breath, dizziness, or fatigue. A research team member certified in first aid and CPR will be on hand, and water will be provided.

BENEFITS OF THE STUDY

You will not receive individual benefit from participating in this study. However, society may benefit from gaining valuable insight into how joint-work distribution changes with varying levels of fatigue. This may assist in the development of exercise programs for fitness and injury prevention as well as assessing injury risk in individuals.

PROTECTION OF RESEARCH INFORMATION

All data collected will be confidential. Your name and email address will be collected and stored in a locked filing cabinet separate from the de-identified biomechanical data collected and the code to identify participants. All electronic data will be stored on a secure network with participant codes in a separate location from the key linking the codes to participant names and will protected via password-protected access. Encryption of all identifiable data will occur for data stored electronically or transmitted via email. The link between your identifier and the research data will be retained for the time period required by the University, and will be shredded or destroyed by 03/01/2025. Government or university staff sometimes review studies such as this one to make sure they are being done safely and legally. If a review of this study takes place, your identifiable data may be examined.

USING YOUR DATA IN FUTURE RESEARCH

The information and/or specimens that we obtain from you for this study might be used for future studies. We will remove anything that might identify you from the information and specimens. If we do so, that information and specimens may then be used for future research studies or given to another investigator without getting additional permission from you.

RESEARCH-RELATED HARMS

In the event of study-related injury, illness, harm, or distress, you may contact Dr. Jeffrey McBride at:

Phone: (828)262-6333
Email: mcbridejm@appstate.edu

In the unlikely event of an adverse event, you will be referred to the emergency room or urgent care for a follow-up. If basic first aid is required, it will be administered by members of the research team. The principal investigator will be present for all sessions and will follow up with you should you complain of any muscle strains.

You or your insurance company will be responsible for any costs for medical care. No other compensation is offered by Appalachian State University for injuries gained due to this study.

By signing this document, you are not waiving any legal rights that you have to act against Appalachian State University for harm or injury resulting from negligence of the University or its investigators.

YOUR RIGHTS AS A RESEARCH PARTICIPANT

Your participation in this research is completely voluntary. If you choose not to participate, there will be no penalty and you will not lose any benefits or rights you would normally have.
If you choose to take part in the research, you can change your mind at any time and stop participating.
If you agree to participate but decide later that you don't want to be in this study, please let the researcher know. If you have questions or concerns about your rights as someone taking part in research, please contact the Appalachian State University Office of Research Protections at **828-262-4060** or **irb@appstate.edu**.

The IRB will insert the approval date (and expiration date, if applicable) here.

Subject's statement

By signing below, I volunteer for this study and agree that:

- The purpose and procedures of the study have been explained to me;
- I have been informed of the risks of participation;
- The study is voluntary, I do not have to participate, and I can withdraw at any time;
- I have been given (or have been told that I will be given) a copy of this consent form to keep.
- I have had the opportunity to ask questions, and was able to get all of my questions satisfactorily answered;
- If I have questions later about the research, or if I have been harmed by participating in this study, I can contact one of the researchers listed on the first page of this consent form.

____

**Printed name of subject Signature of subject

Date_______________

Copies to: Researcher
Subject

Vita

Ceara Larson was born in Bettendorf, Iowa, to Andrew and Jennifer Larson. She graduated from Bettendorf High School in Iowa in May 2017. The following autumn, she entered Lawrence University to study Biology and Physics, and in June 2021 she was awarded the Bachelor of Arts degree. In the fall of 2021, she accepted a graduate assistantship in Exercise Science at Appalachian State University and began her study toward a Master of Arts degree. The M. A. was awarded in May 2023.

Ms. Larson is an alumna of Kappa Kappa Gamma, Zeta Epsilon Chapter and Lawrence University Varsity Fastpitch Softball. She resides in Clearwater, Florida with her dog, Tilly.