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Comparison of Land and Aquatic Loaded Countermovement Jump Landings in Female NCAA Division I Collegiate Athletes

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By

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Abstract

The purpose of this study was to investigate alterations in lower extremity kinematics during the landing phase of a countermovement jump when performed in different environments and under multiple external loads. Twenty-four NCAA Divison I collegiate female athletes performed 12 countermovement jumps on land and 12 jumps in water, submerged to the xiphoid process, for a total of 24 jumps. Within each environmental condition, four loading conditions of three jumps each were performed using a weighted vest: Unloaded, 10%, 20%, or 30% of body mass. The hip, knee, and ankle angles were measured as the smallest angles between the major body segments (trunk, thigh, shank, and foot) in the sagittal plane using the digital goniometer tool from Kinovea video analysis software at the point of maximum knee flexion. Larger angles indicated decreased joint flexion and smaller angles indicated increased joint flexion. The mean hip, knee, and ankle angles were significantly greater for the jump landings in water compared to on land, regardless of load (133.7° vs. 113.9°, 119.5° vs. 107.5°, and 91.7° vs. 85.6°, $p < 0.001$). Independent of environment, the loading conditions also affected the joint angles. The unloaded hip angles were significantly greater than the 10%, 20%, and 30% loaded angles (128.0° vs. 123.3°, 122.5°, and 121.6°, $p < 0.001$) and the unloaded ankle angle was significantly greater than the 10%, 20%, and 30% loaded angles (89.6° vs. 88.5°, 88.4°, and 88.0°, $p = 0.015$, $p = 0.023$, and $p = 0.007$). Increasing lower extremity joint flexion during jump landing may help minimize ACL injury. The decreases in joint flexion during the aquatic jump landings may have occurred due to the off-loading from the buoyancy characteristics of water, which may be less harmful compared to decreased joint flexion on land. The significant increases in joint flexion due to loading condition may provide evidence for use in athlete training programs to help decrease the probability of ACL injury.

Introduction

Anterior cruciate ligament (ACL) injury is one of the most common lower-extremity injuries to occur in athletic competition, especially in females. In a five-year study utilizing the National Collegiate Athletic Association (NCAA) Injury Surveillance System to investigate injury prevalence in collegiate sports, Arendt and Dick (1995) observed that knee injury comprised 19% of all injuries in women's soccer, with ACL injury occurring 31% of the time in all knee injury cases. Over a 16-year period observing injury rates in collegiate female gymnasts, also using the NCAA Injury Surveillance System, knee ligament injuries covered the greatest portion of all injuries during competition at 20% of all injuries. (Marshall, Covassin, Dick, Nassar & Agel, 2007). These high rates have resulted in research focusing on why females are more prone to knee injury (more specifically ACL injury) than males and how to minimize its occurrence.

For instance, risk factors for ACL injury in females include sex-specific anatomical and hormonal differences, different muscle activation patterns, and lower strength and conditioning levels compared to males (Huston & Wojtys, 1996; Hutchinson & Ireland, 1995; Wojtys, Huston, Boynton, Spindler & Lindenfeld, 2002). Female athletes with these risk factors tend to display increased knee joint laxity, leading to greater anterior tibial translation, as well as a high ratio of quadriceps to hamstring muscle activity (Huston & Wojtys, 1996), which may lead to decreased maximum knee flexion during jump landing (Pollard, Sigward & Powers, 2010). Other researchers have discovered additional kinematic and kinetic differences, including increased peak vertical ground reaction forces, decreased hip flexion, increased knee valgus, and increased hip adduction during jump landings (Chappell, Creighton, Giuliani, Yu & Garrett, 2007; Hewett et al., 2005). It has been speculated that when any of these abnormal movements, forces, or muscle activities occur, ACL injury may result.

DeVita and Skelly (1992) conducted a study of drop landings to examine the effect of landing stiffness on joint biomechanics in the lower extremity. They examined eight female collegiate basketball and volleyball players using a video analysis of sagittal plane motion and measured the angle of maximum knee flexion during the landing. From their analyses, DeVita and Skelly reported that two distinct landing styles were employed by the group of participants. The first was a “soft” landing, characterized by a maximum knee flexion angle of less than 63°, and the second was a “stiff” landing, exhibited by those whose maximum knee flexion angles were greater than 103°. Pollard, Sigward, and Powers (2010) investigated these landing styles further by conducting a three-dimensional analysis of drop landings by 58 female club soccer players (ages 11-20) with no history of knee injury. They observed that those who employed a stiff landing style in the sagittal plane also displayed greater knee valgus angles in the frontal plane. It was suggested that during maximum knee flexion, the frontal plane alterations came as a result of the stiff landing that occurred in the sagittal plane, and that these alterations may have an influence on ACL injury in female athletes.

One common exercise used in sport training, lower-extremity injury risk assessment, injury prevention, and rehabilitation is the countermovement jump (CMJ). The CMJ is a double-leg jump characterized by a quick lowering of the center of mass by ankle dorsiflexion, knee flexion, and hip flexion, followed by explosive plantarflexion, knee extension, and hip extension. The landing typically consists of a toe-heel touchdown with ankle, knee, and hip flexion in order to manage impact forces. For training purposes, it is also common for athletes to perform jumps and landings under loaded conditions. Some researchers have suggested external loads applied to the trunk may result in greater hip flexion which may enhance knee stability and ultimately minimize ACL injury (Kulas, Zalewski, Hortobagyi & DeVita, 2008).

Another tool used in injury prevention and rehabilitation is the aquatic environment. The aquatic environment offers distinct advantages over land-based environments, as a result of the alterations of the movements and forces felt by the exerciser. As summarized by Torres-Ronda and Schelling i del Alcázar (2014), water creates a buoyant force which opposes gravitational forces, produces a fluid drag force that provides resistance to movement (Bressel, Dolny, Smith & Miller, 2012), exerts hydrostatic pressure which compresses the body, and retains and transfers heat. These mechanical characteristics often decrease impact ground reaction forces during jumping exercises (Colado et al., 2010; Triplett et al., 2009), reduce pain and stress on the musculoskeletal system while allowing for high intensity training (Bressel, Wing, Miller & Dolny, 2014), and aid circulation and range of motion (Torres-Ronda & Schelling i del Alcázar, 2014; Wang, Belza, Thompson, Whitney & Bennett, 2007). Aquatic training may also provide external sensory feedback through proprioception, which plays a significant role in injury rehabilitation (Wicker, 2011). With these qualities in mind, utilizing exercises such as CMJs in an aquatic environment may lead to adjustments in landing mechanics, including the specific movements associated with ACL injury.

Previous literature has extensively investigated the kinematics of ACL injury, such as lower extremity joint angles during the CMJ on land, but there has been no such research on the effects of the aquatic environment on landing mechanics. Furthermore, the influence of added external loads on lower extremity kinematics in the aquatic environment may be important to investigate because it would provide a novel situation in which new interactions could be observed and the effect of buoyancy could be delineated. Therefore, the purpose of this study was to examine the effects of environmental condition (partial water immersion vs. land) on CMJ landing kinematics about the hip, knee, and ankle. The secondary purpose was to examine the influence of added trunk loads to the same lower extremity kinematics. From the findings of Colado et al. (2010) and Triplett et al. (2009), impact force decreased for jump landings in the aquatic environment, which was attributed to the buoyancy force acting on the body. In the current study, it was expected that decreased ground reaction forces in the aquatic environment would reduce the need for the hip, knee, and ankle to manage excess loading forces, thus influencing the kinematics by decreasing flexion. It was also expected that the added trunk loads would partially counteract the buoyancy force, for which the hip, knee, and ankle would adjust accordingly.

Methods

Participants

Participants were 24 female athletes currently competing at the NCAA Division I level. Half (n = 12) were soccer players (age = 19.8 ± 1.0 years, height = 166.2 ± 4.8 cm, mass = 64.6 ± 6.9 kg), and the remaining half (n = 12) were gymnasts (age = 19.9 ± 1.1 years, height = 160.7 ± 7.9 cm, mass = 62.2 ± 5.7 kg). The two sports were selected due to differences in performance and training requirements of landings. For instance, gymnasts are required to land in a controlled and balanced manner when performing a dismount, or points will be deducted from their score (National Collegiate Athletic Association, 2015). In soccer, landings occur during constant movement and in cutting and stopping motions. Thus, these sport-specific differences for landing may lead to differences in overall mechanics of a CMJ. The participants were free from any current injury that would limit their participation in sport activities at the time of the study and had not required surgery within the past three months. Before participation, they were informed of the procedures of the study and signed an informed consent form approved through the university's Institutional Review Board.

Procedures

In one testing session, participants performed CMJs, which have displayed a high reliability (ICC= 0.98) (Markovic, Dizdar, Jukic & Cardinale, 2004). The jumps were completed in water and on land under four loading conditions: Unloaded, 10%, 20%, and 30% of body mass. The incrementally higher loads up to 30% were included because they are commonly used in athlete training programs and because previous research has discovered that utilizing a 30% of body mass load in jump training may be optimal for power development and performance in high velocity activities on land (McBride, Triplett-McBride, Davie & Newton, 2002). The order of land vs. water environments and load conditions were randomized, however once the land vs. water condition was selected, all loads within that condition were completed before progressing to the next environment. Three trials were performed within each condition for a total of 24 jumps. All testing was conducted at the university's sports medicine facility on an adjustable-height underwater treadmill (Hydroworx 2000; Middletown, PA), with the air and water temperatures maintained at 24°C and 30°C, respectively. For the aquatic environment, the participants were submerged to the xiphoid process, and all jumps were performed without footwear in both environments.

Experimental Protocol

The participants were allowed to perform a small warm-up of bodyweight squats and practice CMJs prior to the actual data collection. They were instructed to place their hands on their hips, and perform hip, knee, and ankle flexion to a self-selected depth for the countermovement, then asked to "jump as high as possible using your natural jumping method," and land on both feet. Jumps that failed to achieve these criteria based on visual observation were repeated.

Each of the loading conditions were completed using a weighted vest (MIR Vest Inc., San Jose, CA) to the nearest 1.4 kg (3 lb) increment for each percentage representing a load equivalent to 10%, 20%, or 30% of body mass. A short rest period of 30-60 seconds was provided between jumps as well as loading conditions in order to adjust the load for the next set of jumps. Kinematic data were gathered using a waterproof high speed digital camera (GoPro model Hero 4, San Mateo, CA) at a resolution of 720p and a sample rate of 120 Hz. The video capture commenced at least two seconds prior to the initiation of the jump and concluded within two seconds after the participant landed and stabilized. It was suggested earlier that sagittal plane hip and knee flexion and ankle dorsiflexion during maximum knee flexion in the sagittal plane are precursory movements to those which occur in the frontal plane (Pollard, Sigward, & Powers, 2010). For this reason, the camera was positioned perpendicular to the sagittal plane on the left side of the participant. Underwater, the camera was mounted to the side of the pool surface using the GoPro waterproof case and suction cup attachment, and in both environments the camera was set at a horizontal distance of about 1.5 m from the participant and a vertical height of 0.5 m.

Data Analysis

The dependent variables measured were the hip, knee, and ankle flexion angles occurring at the instant of maximum knee flexion during the landing. The measurements were computed using the digital goniometer tool from Kinovea video analysis software (version 0.8.15, www.kinovea.org), which was discovered to be highly accurate and reliable through preliminary tests. The validity testing was performed underwater using the GoPro camera to record video of a manual goniometer at various angle measurements held perpendicular to the camera and at the same depth and distance to mimic the position of the participants for the current study. The angles of the manual goniometer were recorded, and then compared to measurements performed and analyzed using the digital goniometer tool in Kinovea (ICC= 0.99, $p < 0.001$).

On the participant's left side, the following landmarks were referenced when positioning the digital goniometer: The fifth metatarsal head, lateral malleolus, fibular head, greater trochanter of the femur, and the acromion process of the scapula. If any landmarks were difficult to identify, the midlines of each body segment were visually discerned and utilized (See Figure 1). The maximum knee flexion angles as well as the hip and ankle flexion angles were measured as the smallest angles between each body segment (trunk, thigh, shank, and foot), and the point of maximum knee flexion was deduced through frame-by-frame visual inspections of each landing. It should be noted that smaller angle measurements indicated greater joint flexion and larger angle measurements indicated decreased joint flexion. The data analysis was performed by one investigator so as to obtain consistent results.

Statistical Analysis

Pre-analysis screening was performed on the raw angle data for each dependent measure to identify any outliers and to test for assumptions of normality. These assessments were determined by visual inspections of the box-and-whisker plots, histograms, Shapiro-Wilk scores, and skewness standard error ratios. Each dependent measure was first analyzed using a 2 (environment [land vs. water]) x 2 (sport [soccer vs. gymnastics]) x 4 (load [unloaded, 10%, 20%, and 30% of body mass]) repeated measures analysis of variance (ANOVA) with SPSS version 24 software (IBM, Chicago, IL). To improve statistical power, if any factor in the 3-way ANOVA displayed no effect or interaction, the model was reduced to a 2-way or 1-way

ANOVA. Any data that violated the assumptions of Sphericity were adjusted according to the Greenhouse-Geisser estimates. If significant main effects were revealed for the load factor, pairwise comparisons were performed using a least significant difference post-hoc assessment. If significant interactions were observed, follow-up *t* tests were performed on the load factor to determine where differences occurred between environments. The alpha level was set at 0.05. To appreciate the meaningfulness of any statistical differences, standard deviations (SD), and 95% confidence intervals (CI) were also included with the means (Table 1).

Results

All participants screened were included in the study except for one from the soccer team whose data could not be analyzed due to technical difficulties with the GoPro camera during data collection. The remaining participants were assessed as planned with no missing data (n = 23). Parametric test assumptions were met on the basis of pre-analysis screening and no outliers were revealed. Additionally, the sport factor (soccer vs. gymnastics) was removed from the statistical model as it displayed no effect or interaction within the 3-way ANOVA.

The ANOVAs for the hip, knee, and ankle angles revealed a significant main effect for the environment (F = 85.8, 41.1, and 82.1, $p < 0.001$) and for the hip and ankle only for the load factors (F = 16.4 and 4.5, $p < 0.001$ and p = 0.006). Significant environment by load interactions for the hip and knee were also observed (F = 4.75 and 4.83, p = 0.005 and 0.012). Follow-up comparisons for the load factor revealed significantly larger hip angles for the unloaded condition compared to the three other loading conditions ($p < 0.001$), and the unloaded ankle angles were significantly larger than the 10%, 20%, and 30% load angles (p = 0.015, 0.023, and 0.007).

Analyses of the loading conditions in each separate environment revealed interesting results (See Table 1, Appendix). On land, the unloaded and 10% loaded hip angles were significantly larger than the 30% load angles (p = 0.028 and 0.023). No significant differences were observed in the knee or ankle. In the aquatic environment, the unloaded hip angle was significantly greater than the 10%, 20%, and 30% loaded angles ($p < 0.001$). The unloaded knee angle was significantly greater than the 10%, 20%, and 30% loaded angles (p = 0.019, 0.013 and 0.001), and the 10% load angle was also significantly greater than the 30% load angle (p = 0.041). For the ankle, the unloaded condition revealed greater angles than the 30% load (p = 0.022).

A follow-up comparison was also performed between environments for each loading condition to investigate the significant environment-load interactions of the hip and knee and locate where the interaction occurred. It was discovered that the mean angles for the aquatic environment were significantly greater than the land environment for each load ($p < 0.05$).

Discussion

Anterior cruciate ligament injury is a common concern among female athletes, due to abnormal movements such as greater hip, knee, and ankle angles during jump landing (Hewett et al., 2005, Pollard, Sigward & Powers, 2010). These kinematic qualities are especially apparent in sports which involve high impact landings. The aim of this study was to examine the effect of the aquatic environment and/or different external loads on lower extremity kinematics in the sagittal plane during a countermovement jump landing. If the aquatic environment or increased loads affected joint angles, they may have merit in aiding in the prevention of ACL injury.

Results indicated hip, knee, and ankle angles increased during landings in water compared to on land, regardless of load. Though earlier studies suggested larger knee angles may lead to greater joint stresses and injury (DeVita & Skelly, 1992; Pollard, Sigward & Powers, 2010), the larger joint angles observed in the aquatic environment may not result in the same stress effects as would be encountered on land. Due to buoyancy of the body in water, researchers have discovered that immersion to the xiphoid process results in a decrease in relative body weight of about 68% (Louder et al., 2014), which reduces the impact forces of landing (Colado et al., 2010; Triplett et al, 2009). The reductions in impact forces were confirmed by Beachem (2016), who discovered a 50.7% decrease in peak force, 53.5% decrease in rate of force development, and 38.6% decrease in impulse for the landings in the aquatic environment compared to the land environment for the same participants in the current study ($p < 0.001$). Therefore, larger joint angles in the aquatic environment may not be as injurious as larger joint angles on land.

With a load added to the trunk, joint angles in water continued to be significantly larger than on land. This may have occurred because the relative weight with the added load (up to 30% of body mass heavier) was less than the offloading due to the buoyancy of the water (about 68% of body mass lighter). Though joint angles were greater in the aquatic environment, training with the reduced loading may be advantageous. The reduced loading may allow for greater specificity in training programs. For example, researchers have discovered aquatic plyometric training to be effective for decreasing muscle soreness while increasing vertical jump height, torque production, and sprint speed in female athletes when compared to training on land (Robinson, Devor, Merrick & Buckworth, 2004).

It is interesting to note that the landings for both environments and each loading condition would be classified as “stiff” as defined by DeVita and Skelly (1992), which consisted of maximum knee flexion angles of 103° or greater. Because of the unique characteristics of the aquatic environment, the defined angles for stiff and soft landings on land may not be applicable in this situation. Further investigation may be warranted to define angle measurements for stiff and soft landings in the aquatic environment independently.

The smaller hip, knee, and ankle angles observed over both environments with each loading factor seem to provide support for the use of external loads in a training or ACL injury prevention program. The unloaded hip and ankle angles were significantly greater than the 10%, 20%, and 30% load angles, though there were no differences between the 10%, 20%, or 30% load angles themselves ($p > 0.05$), which suggests that the lower loads may be sufficient to produce smaller joint angles, compared to the unloaded condition. This is in contrast to the knee angles, where the unloaded and 10% load angles were greater than the 30% load, though no differences were discovered between the unloaded, 10%, and 20% load angles ($p > 0.05$). Therefore, the 30% load may be the most ideal for achieving greater joint flexion overall, but the variability offered by the lower loads may also be beneficial for use in a training program.

Because there was a significant environmental effect on joint angles, further analyses of the load effects were conducted for each environment separately. For the land environment, the hip, knee, and ankle angles were not statistically different between the unloaded and 10% load conditions ($p = 0.418$, 0.389, and 0.064). This result is similar to that of Janssen, Sheppard, Dingley, Chapman and Spratford (2012) who observed no differences in the maximum joint flexion angles between the unloaded and 10 kg (8-12% of body mass) loaded conditions. The lack of significant changes between loads is also supported by data from Beachem (2016), which demonstrated no significant changes in peak force and rate of force development on land ($p > 0.05$), though there was a significant increase in impulse with increased load ($p < 0.001$).

For the current study, the significantly smaller hip angles, which occurred with the 30% load compared to the unloaded jump, indicated an adjustment in landing strategy where the hip may have been used more dynamically than the knee and ankle to manage the increased impulse created by the external load.

The loading conditions in the aquatic environment displayed a greater number of significant changes to joint angles than the land environment. The significant decreases in joint angles with higher loads may indicate the additional downward force created by the load served to counteract the upward buoyancy force. For instance, the 68% weight offload during the unloaded jumps may have decreased to a 38% offload when the external 30% load was applied which may have resulted in a smaller joint angle. This notion is reinforced by the force plate data for the participants, which indicated a significant increase in peak force with increased load in the aquatic environment (Beachem, 2016). For an aquatic training program, the 30% load would seem to be the most ideal because it was the only load factor that significantly decreased joint angles compared to the unloaded condition, though commencing with the 10% added load may be safer for progression to higher intensity jumping, due to higher impact impulse with greater loads.

The follow-up comparisons for each loading condition between environments demonstrated that the mean hip and knee angles were all significantly different which implied no interaction occurred between environment and load. This differs from the results of the ANOVA which established a significant interaction for the hip and knee angles between the environment and load factors (p = 0.005 and 0.012), or in other words, no differences in the angles with the influence of both factors. This discrepancy may have been due to the sample size, which may have been small for the type of statistical analysis used. Post-hoc power analyses for the hip and knee revealed a large effect for the hip (d = 0.882) and a medium-large effect for the knee (d = 0.780), according to the recommended values of 0.80 and 0.50 for large and medium effects (Cohen, 1992). These results indicate the sample size was sufficient to reveal the actual effects of the environment and load conditions on the joint angles. The lack of interaction may have also occurred because the loading factors were not heavy enough to fully counteract the buoyancy forces of the aquatic environment and normalize the participants' relative body weight between the two environments. In that case, a load of about 70% of bodyweight or higher may have been required to affect landing styles and create an interaction between environments, but in the context of this study, heavier loads may not have been feasible for the participants (female gymnasts and soccer players).

Several limitations were present in the current study. First, markers were not used to help identify the bony landmarks for the video analysis. Though this method may be more practical for use in a physical therapy or athletic training environment, the use of markers is ideal for research purposes to maintain accuracy, consistency, and repeatability of measurements. For the current study, the lack of markers as well as the utilization of the open-source Kinovea software may demonstrate the ability to use this video analysis method in an applied setting. Secondly, the video analyses were only conducted for movements in the sagittal plane. Abnormal frontal plane movements have also been noted to influence ACL injury during initial contact (Hewett et al., 2005), so further experimentation observing the frontal plane during maximum knee flexion may also be beneficial. Third, the landing style may have been dependent on the peak height of the CMJ, which was most likely variable between environments and loading factors. To control for this, performing a drop landing from a specified height for all participants may have been more ideal, though it may have reduced the influence of the aquatic environment. It may also be helpful in the future to consider a set order for the environmental condition to control for the effects of different air and water temperatures on joint stiffness and landing mechanics.

Conclusion

Greater joint angles may be a kinematic factor in the incidence of ACL injury during land-based physical activity. Hip, knee, and ankle angles were larger for jump landings in the aquatic environment compared to the land environment. This result may have been due to body weight offloading influenced by the buoyancy characteristics of the aquatic environment, which allowed for decreased impact forces and reduced the need for smaller joint angles. An added trunk load of 30% of body mass displayed significantly smaller hip, knee, and ankle angles over both environments compared to the unloaded condition. Performing loaded jumps may be useful for teaching athletes to increase joint flexion, which may decrease the risk for ACL injury.

References

Arendt, E., & Dick, R. (1995). Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *American Journal of Sports Medicine*, *23*(6), 694-701.

Beachem, P. B. (2016). Effect of increasing external loads on countermovement jump landing kinetics between NCAA D1 women's soccer and gymnastics on land vs in water. (Unpublished Graduate Research). Utah State University, Logan, Utah.

Bressel, E., Dolny, D., Smith, D., & Miller, A. (2012). Aquatic treadmill walking: Quantifying drag force and energy expenditure. *Journal of Sport Rehabilitation.* Technical Report 5, 1-4.

Bressel, E., Wing, J. E., Miller, A. I., & Dolny, D. G. (2014). High-intensity interval training on an aquatic treadmill in adults with osteoarthritis: Effect on pain, balance, function, and mobility. *The Journal of Strength & Conditioning Research*, *28*(8), 2088-2096.

Chappell, J. D., Creighton, R. A., Giuliani, C., Yu, B., & Garrett, W. E. (2007). Kinematics and electromyography of landing preparation in vertical stop-jump risks for noncontact anterior cruciate ligament injury. *American Journal of Sports Medicine*, *35*(2), 235-241.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155.

Colado, J. C., Garcia-Masso, X., González, L. M., Triplett, N. T., Mayo, C., & Merce, J. (2010). Two-leg squat jumps in water: An effective alternative to dry land jumps. *International Journal of Sports Medicine*, *31*(2), 118-122.

DeVita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine & Science in Sports & Exercise*, *24*(1), 108-115.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., ... & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine*, *33*(4), 492-501.

Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular performance characteristics in elite female athletes. *The American Journal of Sports Medicine*, *24*(4), 427-436.

Hutchinson, M. R., & Ireland, M. L. (1995). Knee injuries in female athletes. *Sports Medicine*, *19*(4), 288-302.

Janssen, I., Sheppard, J. M., Dingley, A. A., Chapman, D. W., & Spratford, W. (2012). Lower extremity kinematics and kinetics when landing from unloaded and loaded jumps. *Journal of Applied Biomechanics, 28*(6), 687-693.

Kulas, A., Zalewski, P., Hortobagyi, T., & DeVita, P. (2008). Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. *Journal of Biomechanics*, *41*(1), 180-185.

Louder, T., Bressel, E., Baldwin, M., Dolny, D. G., Gordin, R., & Miller, A. (2014). Effect of aquatic immersion on static balance. *International Journal of Aquatic Research and Education*, *8*(1), 6.

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *The Journal of Strength & Conditioning Research*, *18*(3), 551-555.

Marshall, S. W., Covassin, T., Dick, R., Nassar, L. G., & Agel, J. (2007). Descriptive epidemiology of collegiate women's gymnastics injuries: National Collegiate Athletic Association Injury Surveillance System, 1988–1989 through 2003–2004. *Journal of Athletic Training*, *42*(2), 234.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy-vs. light-load jump squats on the development of strength, power, and speed. *The Journal of Strength & Conditioning Research*, *16*(1), 75-82.

National Collegiate Athletic Association. (2015). 2016 & 2017 NCAA women’s gymnastics rules modifications and meet procedures. Indianapolis, IN: Author.

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics*, *25*(2), 142-146.

Robinson, L. E., Devor, S. T., Merrick, M. A., & Buckworth, J. (2004). The effects of land vs. aquatic plyometrics on power, torque, velocity, and muscle soreness in women. *The Journal of Strength & Conditioning Research*, *18*(1), 84-91.

Torres-Ronda, L., & Schelling i del Alcázar, X. (2014). The properties of water and their applications for training. *Journal of Human Kinetics*, *44*(1), 237-248.

Triplett, N. T., Colado, J. C., Benavent, J., Alakhdar, Y., Madera, J., Gonzalez, L. M., & Tella, V. (2009). Concentric and impact forces of single-leg jumps in an aquatic environment versus on land. *Medicine and Science in Sports and Exercise*, *41*(9), 1790-1796.

Wang, T. J., Belza, B., Thompson, F. E., Whitney, J. D., & Bennett, K. (2007). Effects of aquatic exercise on flexibility, strength and aerobic fitness in adults with osteoarthritis of the hip or knee. *Journal of advanced nursing*, *57*(2), 141-152.

Wicker, A. (2011). Sport-specific aquatic rehabilitation. *Current Sports Medicine Reports*, *10*(2), 62-63.

Wojtys, E. M., Huston, L. J., Boynton, M. D., Spindler, K. P., & Lindenfeld, T. N. (2002). The effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. *The American Journal of Sports Medicine*, *30*(2), 182-188.

Figure 1. Example of angle measurements for data analysis of the land and aquatic landings using the digital goniometer tool from Kinovea. Smaller angles indicated increased joint flexion and larger angles indicated decreased joint flexion.

Table 1

Lower-extremity joint angle measurements for each loading condition within each environment

	Hip (°)		Knee (°)		Ankle (°)	
Environment	M (SD)	CI	M (SD)	CI	M (SD)	CI
Land						
Unloaded	115.8 (15.9)**	[108.9, 122.7]	107.0 (10.6)	[102.4, 111.5]	86.6 (6.0)	[84.0, 89.2]
10%	114.7 (15.4)**	[108.0, 121.3]	107.9 (11.0)	[103.2, 112.7]	85.3 (5.5)	[83.0, 87.7]
20%	113.6 (15.8)	[106.7, 120.4]	108.8 (8.9)	[105.0, 112.6]	85.0 (5.3)	[82.9, 87.1]
30%	111.8 (15.2)	[105.2, 118.3]	106.3 (11.0)	[101.7, 111.2]	85.3 (5.4)	[83.0, 87.6]
Marginal Value	113.9 (15.0)	[107.5, 120.4]	107.5 (9.5)	[103.4, 111.6]	85.6 (5.1)	[83.4, 87.8]
Aquatic*						
Unloaded	140.2 (10.1)[1]	[135.9, 144.6]	123.8 (11.1)***	[119.0, 128.6]	92.6 (4.8)**	[90.5, 94.6]
10%	131.8 (11.1)	[127.0, 136.6]	120.1 (9.7)**	[115.9, 124.3]	91.7 (5.3)	[89.4, 94.0]
20%	131.5 (13.1)	[125.8, 137.2]	116.3 (17.1)	[108.9, 123.7]	91.7 (5.5)	[89.3, 94.1]
30%	131.4 (11.3)	[126.5, 136.3]	117.7 (11.6)	[112.7, 122.7]	90.8 (6.4)	[88.0, 93.5]
Marginal Value	133.7 (10.6)	[129.2, 138.3]	119.5 (11.2)	[114.6, 124.4]	91.7 (5.2)	[89.5, 93.9]

Note. M = mean; SD = standard deviation; CI = 95% confidence interval. Significance values refer to differences between load conditions within each respective environment.

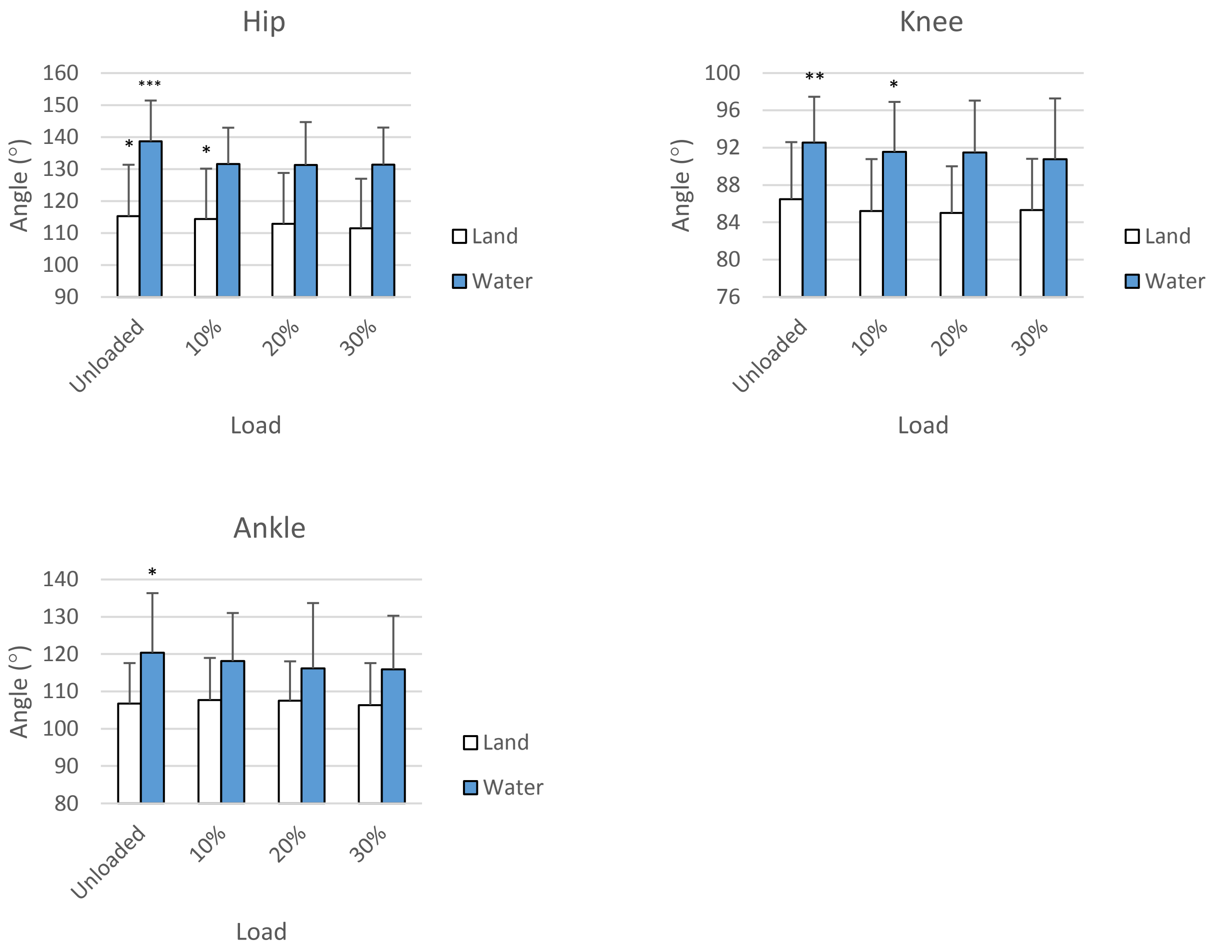
* Joint angles for the aquatic environment are significantly different from the land environment ($p < 0.001$).

** Significantly different from the 30% load condition ($p < 0.05$).

*** Significantly different from the 10%, 20%, and 30% load conditions ($p < 0.05$).

[1] Significantly different from the 10%, 20%, and 30% load conditions ($p < 0.001$).

Appendix



Comparison of hip joint angles between environments and loads. Note. The land condition was significantly different from the aquatic condition ($p < 0.001$).

* Significantly different from the 30% load condition ($p < 0.05$).

** Significantly different from the 10%, 20%, and 30% load conditions ($p < 0.05$).

*** Significantly different from the 10%, 20%, and 30% load conditions ($p < 0.001$).