

Utah State University

DigitalCommons@USU

All Graduate Plan B and other Reports

Graduate Studies

5-2015

Plyometric Landings on Land and in Waist-Deep Water: Comparison Between Young and Middle-Aged Adults

Cade Jon Searle

Follow this and additional works at: <https://digitalcommons.usu.edu/gradreports>

Recommended Citation

Searle, Cade Jon, "Plyometric Landings on Land and in Waist-Deep Water: Comparison Between Young and Middle-Aged Adults" (2015). *All Graduate Plan B and other Reports*. 496.

<https://digitalcommons.usu.edu/gradreports/496>

This Report is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Plan B and other Reports by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.



PLYOMETRIC LANDINGS ON LAND AND IN WAIST-DEEP WATER:
COMPARISON BETWEEN YOUNG AND MIDDLE-AGED ADULTS

By

Cade J. Searle

A plan B research project submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Health and Human Movement

UTAH STATE UNIVERSITY
Logan, Utah
2015

PLYOMETRIC LANDINGS ON LAND AND IN WATER

Abstract

The purpose of this study was to compare dynamic stability and landing kinetics, on land and in water, between young and middle-aged adults performing plyometric exercises. Twenty adults were asked to volunteer: Young = 24.40 ± 2.63 years, $n = 10$ and middle-aged = 46.80 ± 3.05 years, $n = 10$. Participants performed three plyometric exercises (countermovement jump, squat jump, and drop landing) on land and in waist-deep water. Dynamic stability was assessed during landing for each exercise using a time to stabilization (TTS) paradigm. Kinetic measures included time to peak force, peak force, rate of force development (RFD), and impulse. Data were collected via a waterproof force plate positioned on an adjustable-depth pool floor and analyzed with a 2 (age) X 6 (condition) repeated measures ANOVA. Results revealed TTS was greater on land (1.45 ± 0.12 s) than in water (1.35 ± 0.12 s) for two jumps ($p = 0.01$). Peak force, RFD, and impulse were greater on land (33%-36%) ($p < 0.01$). Time to peak force was lower (20%), while normalized peak force (15%) and RFD were greater (28%), in the middle-aged compared to the young group ($p = 0.04$). Results indicate that young and middle-aged adults display improved dynamic stability and are exposed to lower absolute impact forces in water. The effect of age indicates middle-aged participants tend to display greater loading rates and peak forces when compared to the younger group, suggesting landing patterns that may be harmful.

Keywords: aquatic, jumping, dynamic stability, time to stabilization, impact force

Introduction

Plyometrics is a term attributed to Fred Wilt after watching Soviet Olympic athletes perform jumping drills for track and field events, believing the exercises to be the reason for their athletic success (Chu, 1998). Plyometrics utilize what is referred to as the stretch-shortening cycle (SSC). The SSC involves a rapid eccentric muscle action, followed by a rapid concentric action of the same muscle-tendon unit (Komi, 1993). The SSC, a key feature of plyometrics, is believed to enhance muscle force and power production during the concentric phase of a given movement when compared to a muscle action only including a concentric action (Komi, 1993).

Although there is some disagreement as to the effectiveness of plyometric training from a sport performance perspective, researchers have provided evidence for plyometrics as a mode of exercise for improving various aspects of human performance and possibly reducing the risk of injuries (Markovic & Mikulic, 2010). For example, a recent meta-analysis by Markovic and Mikulic (2010) on lower-body plyometrics reported muscular contractile performance, hypertrophy, muscle geometry, neural adaptations, strength, power, agility, and jumping performance were all improved regardless of fitness level or age after completing a plyometric training program. Additionally, observations reveal plyometric training in an aquatic environment yields similar results to an equivalent land-based plyometric training program (Arazi & Asadi, 2011; Markovic & Mikulic, 2010; Robinson, Devor, Merrick, & Buckworth, 2004; Stemm & Jacobson, 2007). The clinical efficacy of plyometric training in water is apparent with less soreness and possibly less injury risk due to buoyant forces and viscosity that decrease impact forces during jump landings (Colado et al., 2010; Donoghue, Shimojo, & Takagi, 2011; Martel, Harmer, Logan, & Parker, 2005; Miller et al., 2007; Robinson et al., 2004). The lower impact forces observed during aquatic plyometric training may be an attractive feature for older

PLYOMETRIC LANDINGS ON LAND AND IN WATER

adults who wish to maintain muscle power, which is critical for reducing fall risk as age increases (Reid & Fielding, 2012).

Currently, most research involving aquatic plyometric training has focused on athletic performance benefits in younger, not older, participants. Research observing aquatic plyometrics in older adults may be particularly beneficial given that falls and decreased mobility are two of the major health risks associated with ageing (Liu et al., 2006; Reid & Fielding, 2012). A study of middle-aged participants may be a useful proxy, due to their higher retention of muscle power, for studying elderly populations (Macaluso & DeVito, 2004). Muscle power, the product of muscle force and velocity, is a critical variable in determining functional performance in older adults with limited mobility and has been shown to increase via plyometric training, improving mobility and decreasing fall risk (Liu et al., 2006; Markovic & Mikulic, 2010; Reid & Fielding, 2012).

Ground reaction force (GRF) values, captured from a force platform, can be used to quantify and measure dynamic stability and the landing forces associated with the different phases of a plyometric jump. Dynamic stability is the ability to correct disturbances in balance (Ebben, Vanderzanden, Wurum, & Petushek, 2010b; Liu & Heise, 2013; Ross & Guskiewicz, 2003). Time to stabilization (TTS) is a quantifiable force plate measure used to evaluate dynamic stability and is shown to be reliable and valid for this purpose, revealing how quickly the neuromuscular system can utilize sensory and mechanical systems to safely land from a jump and return to stability (Ebben et al., 2010b; Fransz, Huurnink, de Boode, Kingma, & van Dieen, 2015; Liu & Heise, 2013, Ross & Guskiewicz, 2003; Ross, Guskiewicz, Prentice, Schneider, & Yu, 2004; Ross, Guskiewicz, & Yu, 2005; Wikstrom, Powers, & Tillman, 2004). As previously noted, studies have compared the landing force differences between land and aquatic plyometrics

PLYOMETRIC LANDINGS ON LAND AND IN WATER

and found measures such as time to peak force, peak force, rate of force development, and impulse to be greater on land than in water (Colado et al., 2010; Donoghue et al., 2011; Ebben, Flanagan, Sansom, Petushek, & Jensen, 2010b). Again, these studies are limited since they did not include older adults who are likely to benefit from plyometric training. A study focusing on a comparison of dynamic stability and landing forces in different age groups, environments, and plyometric jumps is needed to provide strength and conditioning professionals and clinicians with evidence to improve plyometric exercise prescriptions.

Accordingly, the purpose of this study was to compare dynamic stability and landing forces (see *Table 1* in the appendix), on land and in waist-deep water, between young and middle-aged adults performing plyometric exercises. Based on environmental conditions, we hypothesized dynamic measures of stability (e.g. TTS) would be greater in the water than on land. We also hypothesized landing forces would be reduced in the aquatic environment versus on land due to the water's unique properties (e.g. buoyancy, viscosity). TTS results could potentially indicate which environment serves as a more effective stability-training aid in developing dynamic stability, and the expected reduced landing forces in water could indicate which environment is safer for plyometrics in middle-aged adults. Age-related hypotheses were based on the decreased muscular power of older adults (Macaluso & DeVito, 2004), where we expected to see greater TTS values and higher impact forces for middle-aged than younger participants.

Methods

Participants

Twenty adults between 18 and 50 years of age were asked to participate. Participants were separated into a “young” (5 male, 5 female, age: 24.40 ± 2.63 years, height: 172.34 ± 10.49 cm, land mass: 73.99 ± 8.26 kg, water mass: 42.70 ± 6.49 kg) or “middle-aged” (5 male, 5

PLYOMETRIC LANDINGS ON LAND AND IN WATER

female, age: 46.80 ± 3.05 years, height: 173.23 ± 10.54 cm, land mass: 76.36 ± 19.35 kg, water mass: 49.58 ± 16.15 kg) group based on age (young: 18-30 years, middle-aged: 40-50 years).

Participants were recruited from a University's campus and surrounding areas. The age limit of 50 years was chosen to ensure the safety of participants since previous research has indicated that muscle power decreases drastically after this age (Macaluso & DeVito, 2004). The decrease in power may substantially increase the injury risk for these individuals, so we collected data on middle-aged adults who theoretically have the ability to safely complete plyometric exercises in both environments (Arazi & Asadi, 2011; Colado et al., 2010). Participants were included if they reported no physical impairment or recent history of lower-limb injury that could increase injury risk or impact their ability to perform plyometric jumping exercises on land and in water.

Exclusion criteria was self-reported and included any form of lower-limb, core-strength, or neurological injury/disability such as bone diseases, muscle/tendon impairments, arthritis, low back pain, and Parkinson's disease. Participants signed an informed consent form approved by the university institutional review board.

Procedures

Participants were asked to perform three common plyometric exercises. Two jumps (countermovement and squat jump) and one drop landing exercise were performed in accordance with the National Strength and Conditioning Association's standards (Baechele & Earle, 2008; Irmischer et al., 2004). Participants were given instructions orally and by example in addition to practicing the counter-movement jump, squat jump, and drop landing. Practice took place for familiarization before data collection in each environment. A full description of the technique and purpose of each movement is provided in *Table 2* in the appendix. Additional verbal cues given for the jumps were to "jump as explosively as possible, then land and stabilize" whereas

PLYOMETRIC LANDINGS ON LAND AND IN WATER

the drop landing instructions were to “step off and stabilize”. Each exercise was performed three times on the same rigid surface on dry land and in water at greater trochanter standing height on the force platform. Initial environment was randomized so participants either started on land or in the water, and all the jumps within the environment were randomized and completed before moving on to the next environment. Greater trochanter water level was used as the landing height for all jumps because proper squat and countermovement jump techniques would completely submerge the subject underwater if a xiphoid water depth was used. Land jumps were completed wearing shoes while aquatic jumps were completed barefoot. The reasoning behind the footwear protocol was that in a real-world environment, people are more prone to wear shoes on land and go barefoot in the water. Land and aquatic jumps were executed on the same waterproof force platform (AMTI, Model OR6-WP, Watertown, MA) that was placed on an adjustable-depth treadmill platform (HydroWorx 2000, Middletown, PA).

Data Collection and Analysis

Force platform hardware was calibrated before testing and reset for each environment condition, and the force platform was tared before each jump. Impact force data were collected via NetForce software (AMTI). The software was manually triggered to record 20 seconds of data (1000Hz), enough time for participants to complete a full jump. Data were filtered with initial landing occurring at a RFD of 10,000 Newtons per second between two successive data points. This is because initial contact is more difficult to identify underwater due to the gradual increase in vertical force before a more exponential increase. This method has been shown to be accurate to 0.02 seconds compared to video analysis (Donoghue et al., 2011). Data were analyzed in Microsoft Excel (Microsoft Corp., Redmond, WA) before being calculated into the

PLYOMETRIC LANDINGS ON LAND AND IN WATER

following absolute and normalized, if applicable, dependent measures for the landing phase:

TTS, time to peak force, peak force, rate of force development (RFD), and impulse.

TTS was calculated from the dampening of GRF fluctuations over time. We followed the procedures outlined by Liu and Heise (2013) in our analysis which calculated TTS as described in *Figure 1* using *Equation 1* that was modified to fit our data collection, which included more data points due to the increased frequency of collection. Data after the initial landing point was considered for TTS analysis, which continued for 10 seconds after the threshold was met (Liu & Heise, 2013). The sequential averaging was performed using Python (Python Software Foundation, Beaverton, OR) to expedite this process, and Excel was used to determine the point where the sequential average diminished to within one quarter of the overall standard deviation using logical functions (Liu & Heise, 2013).

The landing impact measures chosen mimicked those done by Donoghe et al. (2011) that observed all the dependent measures as normalized to body weight, with the exception of TTS. In our study, these measures are reported absolute and normalized for each participant via body weight (Newtons), measured by the force platform when data were collected. Land and water body weights were used accordingly to the environment the jumping trial took place in. *Table 1* in the appendix describes how each of these variables were calculated.

Statistical Analysis

Dependent measures (TTS, time to peak force, peak force, RFD, and impulse), both absolute and normalized, were analyzed using a 2 (age) x 6 (condition) Repeated Measures Analysis of Variance (ANOVA) with SPSS version 21 software (IBM, Chicago, IL). The repeated measures ANOVA was performed for each variable with age and condition as independent variables. This reported any significant main effects ($\alpha = 0.05$) between age groups

PLYOMETRIC LANDINGS ON LAND AND IN WATER

or between jump types and their environment. Within subject effects were also tested to observe if any age and dependent variable interactions were present. Cohen's *d* effect sizes were assessed to find the meaningfulness of any significant differences.

Results

TTS

TTS was significantly different between environments for the countermovement (CM) ($p = 0.03$, effect size [ES] = 0.79) and squat jump (SJ) ($p = 0.04$, ES = 0.72), but not for drop landing (DL) ($p = 0.33$) (Figure 1.A). There was no difference in TTS between young and middle-aged participants ($p = 0.99$) (Figure 2.A), nor was there an interaction between the age groups ($p = 0.51$).

Time to Peak Force

Time to peak force was not significantly different between environments for any of the jumps (CM; $p = 0.86$, SJ; $p = 0.94$, DL; $p = 0.07$) (Figure 1.B). However, there was a significant difference between young and middle-aged participants ($p = 0.04$, ES = 0.90) (Figure 2.B). There was no age related interaction for time to peak force ($p = 0.34$).

Peak Force

Peak force was significantly different between environments for the CM ($p < 0.01$, ES = 1.06), SJ ($p < 0.01$, ES = 1.15), and DL ($p < 0.01$, ES = 1.17) (Figure 1.C). There were no differences in peak force between age groups ($p = 0.09$) (Figure 2.C), nor was there an interaction between ages ($p = 0.39$). Normalized peak force was not significantly different between environments for any of the jumps (CM; $p = 0.06$, SJ; $p = 0.33$, DL; $p = 0.27$) (Figure 1.D). However, there was a difference between age groups ($p = 0.03$, ES = 1.02) (Figure 2.D). There was no age related interaction for normalized peak force ($p = 0.34$).

PLYOMETRIC LANDINGS ON LAND AND IN WATER

RFD

RFD was significantly different between environments for the countermovement jump ($p < 0.01$, ES = 0.59), squat jump ($p < 0.01$, ES = 0.62), and drop landing ($p < 0.01$, ES = 0.89) (Figure 1.E). There was also a difference between age groups ($p = 0.04$, ES = 1.01), but no interaction within the age groups ($p = 0.49$). Normalized RFD was not significantly different between environments for any of the jumps (CM; $p = 0.27$, SJ; $p = 0.25$, DL; $p = 0.86$) (Figure 1.F). There was a difference between age groups ($p = 0.04$, ES = 0.98) (Figure 2.F), but no interaction within the age groups ($p = 0.45$).

Impulse

Impulse was significantly different between environments for the countermovement jump ($p < 0.01$, ES = 1.29), squat jump ($p < 0.01$, ES = 1.36), and drop landing ($p < 0.01$, ES = 1.38) (Figure 1.G). There was no difference between ages for impulse ($p = 0.67$), nor any interaction within the age groups ($p = 0.57$). Normalized impulse was not significantly different between environments for any of the jumps (CM; $p = 0.28$, SJ; $p = 0.89$, DL; $p = .24$) (Figure 1.H). There was no difference between age groups ($p = 0.75$) (Figure 2.H), nor any interaction within the ages ($p = 0.95$).

Discussion

The purpose of this study was to compare dynamic stability and landing forces, on land and in waist-deep water, between young and middle-aged adults performing plyometric exercises. Our study is the first we know of to determine the effect of aquatic plyometric exercise on middle-aged adults using multiple kinetic and temporal outcome measures, such as dynamic stability or TTS.

Our results for TTS are consistent with previous research on land (Franz et al., 2015) and indicate that properties of water may actually contribute to shorter stabilization times (*Figure*

PLYOMETRIC LANDINGS ON LAND AND IN WATER

1.A) or improved dynamic stability during the countermovement and squat jump. We hypothesized that TTS values would be greater in water because preprogrammed landing mechanics would be affected by properties of water such as buoyancy, which influences static stability in chest deep water (Louder et al., 2014). Lower TTS values in water than land may be explained by enhanced proprioceptive body awareness that hydrostatic pressure and viscosity of water provides (Roth, Miller, Richard, Ritenour, & Chapman, 2006). Indeed, it could also be argued TTS values were lower in water due to lower peak force values within the aquatic environment (Colado et al., 2010; Donoghue et al., 2011; Martel et al., 2005; Miller et al., 2007; Robinson et al., 2004) since it may be easier to stabilize after a lower impact force. However, post-analysis linear regression indicated no significant relationship was observed between peak force and TTS (*Figure 3*).

Although the environment affected TTS values for the countermovement and squat jump, there was no difference between environments for the drop landing exercise (*Figure 1.A*). This observation may be attributed to the lack of a propulsive take-off phase, requiring less skill to complete the exercise, which has been speculated to achieve lower TTS values (Ebben et al., 2010b). Our instructions, provided in the methods, to the participant for the jumps versus the drop landing help to illustrate this point. For example, the jumping exercises require an explosive takeoff before landing and stabilizing whereas the drop landing merely requires the participant to step off the platform and stabilize.

While there were differences in TTS between environments, there were no differences between age groups (*Figure 2.A*), nor any interaction. These results contradict our hypothesis, yet may be a function of the middle-age group used in our study. For example, researchers examining other measures of dynamic stability (e.g., timed up-and-go) have observed that older

PLYOMETRIC LANDINGS ON LAND AND IN WATER

adults (e.g., > 60 years of age) tend to display inferior dynamic stability when compared to younger adults, whereas middle-aged adults display no differences (Hollman, Kovash., Kubik, & Linbo, 2007). The latter indicates that our middle-aged group may not have experienced a sufficient age-related decline in musculoskeletal and sensorimotor systems that affect dynamic stability (Hollman et al., 2007). Future research may wish to examine the decline of dynamic balance in an older population as they age, and how aquatic exercise may slow or reverse this trend.

Results for landing kinetics displayed mixed results between environments and age. For example, time to peak force was not different between environments whereas impact forces were greater on land than in water (*Figure 1.B.C.E.G*). The values for the former are comparable to previous research in untrained participants completing drop landings on land (Seegmiller & McCaw, 2003). Peak forces in our study were 33% lower in water than land, which is somewhat different from previous studies observing approximately a 62% and 59% decrease (Colado et al., 2010; Ebben et al., 2010a). However, these previous studies used water depths at chest-level when landing (Colado et al., 2010; Ebben, et al., 2010a). As would be expected, the higher water level upon impact increases the buoyant force that likely contributed to the discrepancy. RFD and impulse were greater on land than in water which is consistent with the peak force value trends (*Figure 1.C.E.G*). It can be observed from these results how effective the buoyant and viscous properties of water are, dramatically reducing impact forces during landing, and possibly lowering the risk of lower extremity injury (Mizrahi & Susak, 1982; Zadpoor & Nikooyan, 2011).

Regarding the normalized force values, we observed no differences between land and water trials (*Figure 1.D.F.H*). These results are expected because when a person is placed in

PLYOMETRIC LANDINGS ON LAND AND IN WATER

water, not only do landing force values decrease, their body weight decreases proportionately.

This expectation is not consistent with the observations made by Donoghue et al. (2011).

However, our normalized values on land are more in line with previous research for normalized peak force (McNair & Prapavessis, 1999) and impulse (Seegmiller & McCaw, 2003). Our normalized RFD values were half of what others have reported on land, but this may be due to their drop height being twice as high from ours (Irmischer et al., 2004). It can be observed from our results how impact forces are similar on land and in water in terms of body weight (*Figure 1.D.F.H*), indicating a proportional decrease in landing forces as body weight decreases from land to water. However, absolute force differences indicate how the environment may change the amount of impact forces enacted upon the body when landing, possibly lowering the risk of injury from land to water (*Figure 1.C.E.G*).

Comparing impact forces between age groups was an important objective of this study. Results indicated that time to peak force was greater for the young group, while normalized peak force and absolute and normalized RFD were less in the young group (*Figure 2.B.D.F*). These results support our hypothesis that the middle-aged group would experience greater impact forces upon landing, based on the possible regression of muscular power or skill as people age (Macaluso & DeVito, 2004). While the amount of impulse to slow momentum was similar between the ages, how they reached that level of impulse was different between the two age groups. The young group was able to spread the force over a longer period of time, at a slower rate, and with a lower peak force, indicating the landing pattern was softer than their middle-aged counterparts. A softer landing pattern has been speculated to decrease incidences of injury and slow joint degeneration (Mizrahi & Susak, 1982; Zadpoor & Nikooyan, 2011).

PLYOMETRIC LANDINGS ON LAND AND IN WATER

Implications of this research apply to athletic, rehabilitative, and training professionals. Since TTS was not different between age groups, and with shorter stabilization times in water than on land, water could be a good first step in training dynamic stability before progressing to more advanced stability training exercises on land. Physical attributes such as strength, power, and neural adaptations, regardless of age or fitness level, have shown similar increases after land and water-based plyometric training (Markovic & Mikulic, 2010). Results of the current study may support this observation as evidenced by the normalized force values in *Figure 1.D.F.H.* Furthermore, the dramatically reduced absolute impact forces observed in water could possibly make plyometrics safer and easier for aging individuals. Practitioners could potentially utilize an aquatic environment to reduce impact forces during exercise as evidenced in *Figure 1.C.E.G.* Aquatic plyometrics may help improve and recondition components of muscular power that will improve mobility and decrease fall risk for middle-aged adults as they age (Liu et al., 2006; Reid & Fielding, 2012), but this conjecture will need to be formally tested.

There are some limitations of this study. First, we only analyzed TTS in the vertical axis as opposed to measuring TTS in the mediolateral and anteroposterior axes as well. However, pilot testing before the study revealed no significant differences in mediolateral or anteroposterior TTS since the movement in these axes was minimal given the jumps in this study were predominantly in the vertical direction. Our pilot testing supports claims made by Liu and Heise (2013) that jump-landing direction is most influential in determining which axes have the longest and more important TTS value. Another limitation was the different footwear protocol for each environment. We justified our reasoning by concluding that in a practical setting, people will wear their own shoes for land exercises and probably go barefoot for water exercises due to the lack of availability and price of water-specific footwear. The effect of

PLYOMETRIC LANDINGS ON LAND AND IN WATER

training on landing forces was not studied in our experiment, but previous research might suggest lower landing forces after a plyometric training program (Irmischer et al., 2004).

Future research may benefit from studying physical and mechanical outcome measures while jumping across different age, health, and gender groups in cross-sectional and longitudinal designs with training studies. Our study leads the way to studying these different conditions by studying healthy participants across two age groups that have not been studied in comparison before. Our middle-aged group could be a useful proxy to studying elderly populations. None of our middle-aged participants reported any pain or injuries in the aquatic environment, and many commented, unprompted, that they preferred jumping in the water because it reduced their fear of falling. Coupling these subjective observations with objective results of the study, plyometrics in the water may be appropriate for elderly populations. Mechanical and physiological responses to different water levels could also be studied to indicate optimal water heights dependent upon a participant's goals.

Conclusion

Our findings showcase the differences in dynamic stabilization and landing forces between different environments and age groups. Our measure of dynamic stabilization (TTS) was lower in water than it was on land, with no difference between the younger and middle-aged groups. This may indicate that regardless of age, an aquatic environment may be a good first step in training dynamic stability. Landing forces were lower in water than on land, and our younger group landed more softly than the middle-aged group. Environmental observations may point toward aquatic plyometrics being safer than land-based plyometrics. Age-related observations may indicate that older adults could benefit most from the decreased landing impacts an aquatic environment may provide.

References

- Arazi, H., & Asadi, A. (2011). The effect of aquatic and land plyometric training on strength, sprint, and balance in young basketball players. *Journal of Human Sport & Exercise*, 6(1), 101-111. doi: 10.4100/jhse.2011.61.12
- Baechle, T. R., & Earle, R. W. (2008). *Essentials of strength training and conditioning* (3rd ed.). Champaign, IL: Human Kinetics.
- 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. *The American Journal of Sports Medicine*, 35(2), 235-241. doi: 10.1177/03635465062940077
- Chu, D. A. (1998). *Jumping into plyometrics*. (3rd ed.). Champaign, IL: Human Kinetics.
- 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. doi: 10.1055/s-0029-1242814
- Donoghue, O. A., Shimojo, H., & Takagi, H. (2011). Impact forces of plyometric exercises performed on land and in water. *Sports Health: A Multidisciplinary Approach*, 3(3), 303-309. doi: 10.1177/1941738111403872
- Ebben, W., Flanagan, E., Sansom, J., Petushek, E., & Jensen, R. (2010a). *Ground reaction forces of variations of plyometric exercises on hard surfaces, padded surfaces, and in water*. Paper presented at The 28th Conference of the International Society of Biomechanics in Sports: Coaching and Sports Activities, Marquette, Michigan, USA. doi: 10.1519/JSC.0b013e318182034b

PLYOMETRIC LANDINGS ON LAND AND IN WATER

- Ebben, W. P., Vanderzanden, T., Wurum, B. J., & Petushek, E. J. (2010b). Evaluating plyometric exercises using time to stabilization. *Journal of Strength and Conditioning Research*, 24(2), 300-306. doi: 10.1519/JSC.0b013e318182034b
- Fransz, D. P., Huurnink, A., de Boode, V. A., Kingma, I., & van Dieen, J. H. (2015). Time to stabilization in single leg drop jump landings: An examination of calculation methods and assessment of differences in sample rate, filter settings and trial length on outcome measures. *Gait & Posture*, 41(1), 63-69. doi: 10.1016/j.gaitpost.2014.08.018
- Hollman, J. H., Kovash, F. M., Kubik, J. J., & Linbo, R. A. (2007). Age-related differences in spatiotemporal markers of gait stability during dual task walking. *Gait & Posture*, 26(1), 113-119. doi: 10.1016/j.gaitpost.2006.08.005
- Irmischer, B. S., Harris, C., Pfeiffer, R. P., DeBeliso, M. A., Adams, K. J., & Shea, K. G. (2004). Effects of a knee ligament injury prevention exercise program on impact forces in women. *Journal of Strength and Conditioning Research* 18(4), 703-707.
- Komi, P. V. (1993). *Strength and power in sport* (2nd ed.). Oxford, UK: Blackwell scientific publications.
- Liu, K., & Heise, G. D. (2013). The Effect of Jump-Landing Directions on Dynamic Stability. *Journal of Applied Biomechanics*, 29(5), 634-638.
- Liu, Y., Peng, C. H., Wei, S. H., Chi, J. C., Tsai, F. R., & Chen, J. Y. (2006). Active leg stiffness and energy stored in the muscles during maximal counter movement jump in the aged. *Journal of Electromyography and Kinesiology*, 16(4), 342-351. doi: 10.1016/j.jelekin.2005.08.001

PLYOMETRIC LANDINGS ON LAND AND IN WATER

- 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), 53-65.
- Macaluso, A., & DeVito, G. (2004). Muscle strength, power and adaptations to resistance training in older people. *European Journal of Applied Physiology*, 91, 450-472. doi: 10.1007/s00421-003-0991-3
- Markovic, G., & Mikulic, P. (2010). Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Medicine*, 40(10), 859-895. doi: 10.2165/11318370-000000000-00000
- Martel, G. F., Harmer, M. L., Logan, J. M., & Parker, C. B. (2005). Aquatic plyometric training increases vertical jump in female volleyball players. *Medicine and Science in Sports and Exercise*, 37(10), 1814-1819. doi: 10.1249/01.mss.0000184289.87574.60
- McNair, P. J., & Prapavessis, H. (1999). Normative data of vertical ground reaction forces during landing from a jump. *Journal of Science and Medicine in Sport*, 2(1), 86-88.
- Miller, M. G., Cheatham, C. C., Porter, A. R., Ricard, M. D., Hennigar, D., & Berry, D. C. (2007). Chest-and waist-deep aquatic plyometric training and average force, power, and vertical-jump performance. *International Journal of Aquatic Research & Education*, 1(2), 145-155.
- Mizrahi, J., & Susak, Z. (1982). Analysis of parameters affecting impact force attenuation during landing in human vertical free fall. *Engineering in Medicine*, 11(3), 141-147.
- Reid, K. F., & Fielding, R. A. (2012). Skeletal muscle power: a critical determinant of physical functioning in older adults. *Exercise and Sport Sciences Reviews*, 40(1), 4-12. doi: 10.1097/JES.0b013e31823b5f13

PLYOMETRIC LANDINGS ON LAND AND IN WATER

- 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.
- Ross, S., & Guskiewicz, K. (2003). Time to stabilization: A method for analyzing dynamic postural stability. *International Journal of Athletic Therapy and Training*, 8(3), 37-39.
- Ross, S., Guskiewicz, K., Prentice, W., Schneider, R., & Yu, B. (2004). Comparison of biomechanical factors between the kicking and stance limbs. *Journal of Sport Rehabilitation*, 13(2), 135-150.
- Ross, S., Guskiewicz, K., & Yu, B. (2005). Single-leg jump-landing stabilization times in subjects with functionally unstable ankles. *Journal of Athletic Training*, 40(4), 298-304.
- Roth, A. E., Miller, M. G., Richard, M., Ritenour, D., & Chapman, B. L. (2006). Comparisons of static and dynamic balance following training in aquatic and land environments. *Human Performance and Health Education Faculty Research*, Paper 5.
http://scholarworks.wmich.edu/humanperformance_faculty/5.
- Seegmiller, J. G., & McCaw, S. T. (2003). Ground reaction forces among gymnasts and recreational athletes in drop landings. *Journal of Athletic Training*, 38(4), 311-314.
- Stemm, J. D., & Jacobson, B. H. (2007). Comparison of land-and aquatic-based plyometric training on vertical jump performance. *The Journal of Strength & Conditioning Research*, 21(2), 568-571.
- Wikstrom, E. A., Powers, M. E., & Tillman, M. D. (2004). Dynamic stabilization time after isokinetic and functional fatigue. *Journal of Athletic Training*, 39(3), 247-253.

PLYOMETRIC LANDINGS ON LAND AND IN WATER

Zadpoor, A. A., & Nikooyan, A. A. (2011). The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review. *Clinical Biomechanics*, 26(1), 23-28. doi: 10.1016/j.clinbiomech.2010.08.005

PLYOMETRIC LANDINGS ON LAND AND IN WATER

Appendix

Table 1. List of dependent variables with simple definitions and positive value trends. *Reported via absolute value or normalized to body weight measured in the environment the trial took place in. ¹; Liu & Heise (2013). ²; Markovic & Mikulic (2010).

Dependent Variable of Dynamic Stability	Calculation	Positive Value Trend
Time to Stabilization (TTS)	Time for sequential average (<i>Equation 1</i>) to diminish within ¼ of the overall standard deviation. ¹	Lower may be safer ²
Dependent Variables of Landing Impact		
Time to Peak Force	Time from initial landing to the point peak force is observed	Higher may be safer ²
Peak Force*	Greatest force value observed	Lower may be safer ²
Rate of Force Development *	Slope of peak force over the time to peak force	Lower may be safer ²
Impulse*	Product of the integral sum of force, from point of impact to body weight after reaching peak force, and time	Lower may be safer ²

Table 2. List of plyometric exercises, their purpose, and correct technique. SSC; stretch-shortening cycle. ¹;

Plyometric Jumps	Purpose	Technique
Countermovement Jump	A fluid, unrestricted jumping motion that utilizes the SSC	Start in upright position, squat down, and jump with hands positioned on hips
Squat Jump	A restricted jumping motion that does not utilize the SSC	Start by holding an approximate knee angle of 90° before jumping with hands positioned on hips
Landing Exercise		
Drop Landing	A landing movement that does not have a take-off phase	Start on a platform 30cm higher ¹ than the force plate, step off, and land on the force plate with hands positioned on hips
Donoghue et al. (2011).		

Equation 1. Sequential averaging equation (Liu & Heise, 2013)

$$SeqAvgx(n) = \frac{\sum_{n=1}^{10001} Fz}{n}$$

PLYOMETRIC LANDINGS ON LAND AND IN WATER

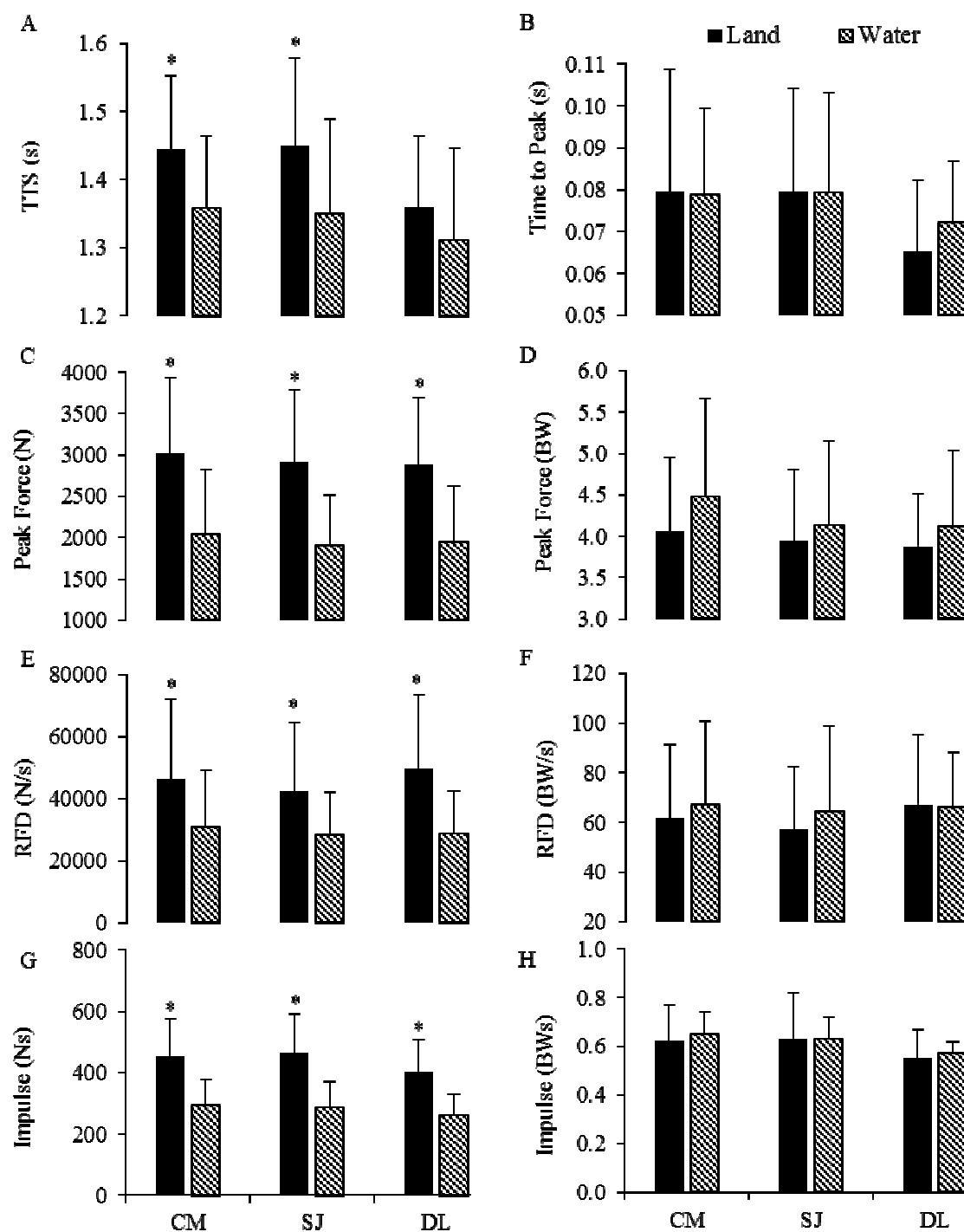


Figure 1. Comparison of environment among jump types with young and middle-aged samples grouped together for all dependent measures. CM; countermovement jump. SJ; squat jump. DL; drop landing. RFD; rate of force development. BW; newtons normalized to body weight. TTS; time to stabilization. * denotes statistical significance at $p < 0.05$.

PLYOMETRIC LANDINGS ON LAND AND IN WATER

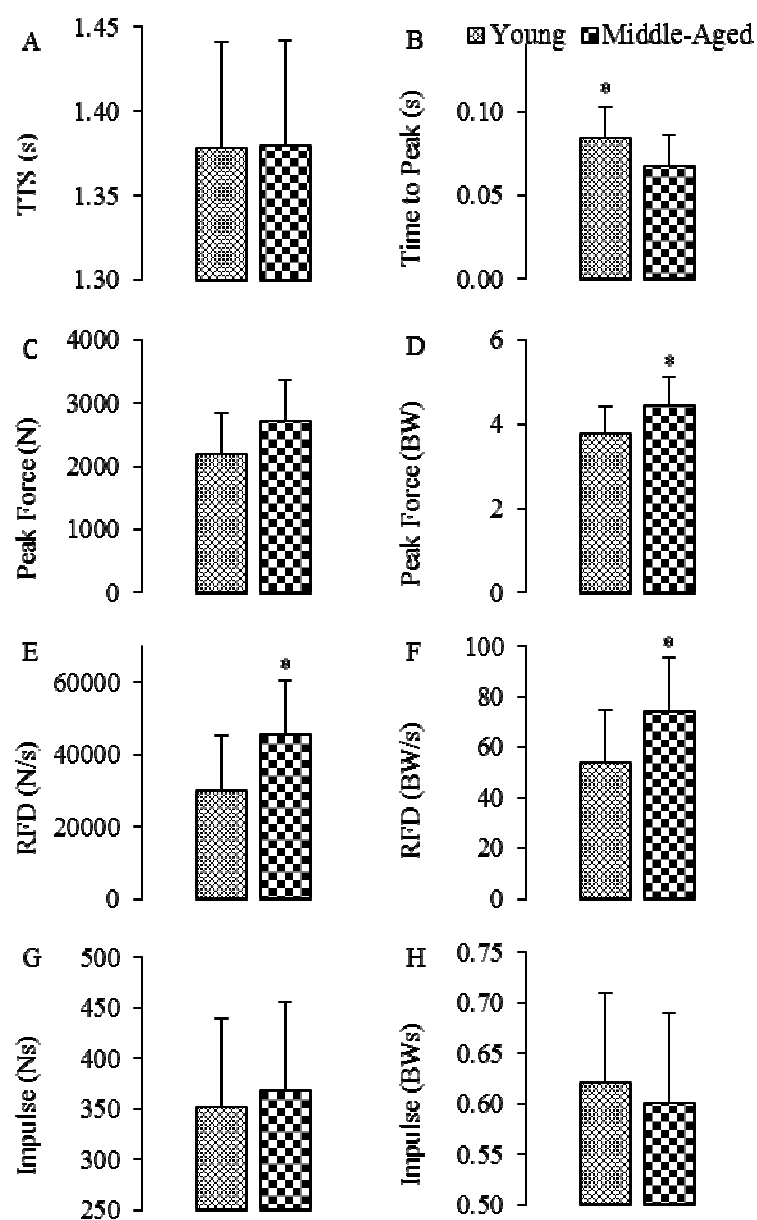


Figure 2. Comparison of young and middle-aged subjects with environment and jump types grouped together for all dependent measures. RFD; rate of force development. BW; newtons normalized to body weight. TTS; time to stabilization. * denotes statistical significance at $p < 0.05$.

PLYOMETRIC LANDINGS ON LAND AND IN WATER

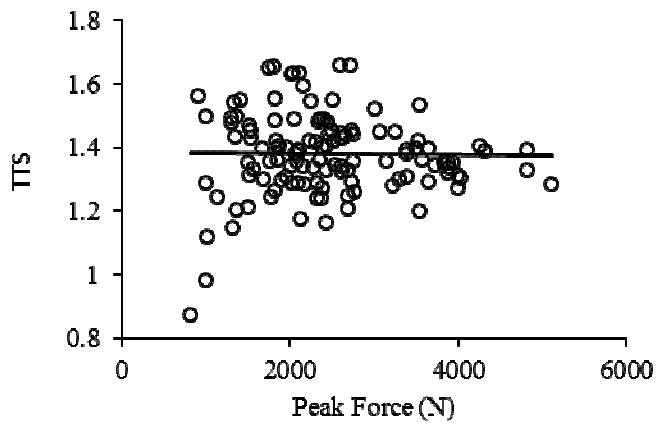


Figure 3. Linear regression showing the lack of a significant relationship between peak force (predictor variable) and TTS (response variable) ($F = 0.02$, $p = 0.89$, $R^2 < 0.01$).