[Sports Physical Therapy]

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Impact Forces of Plyometric Exercises Performed on Land and in Water

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Background: Aquatic plyometric programs are becoming increasingly popular because they provide a less stressful alternative to land-based programs. Buoyancy reduces the impact forces experienced in water.

Purpose: To quantify the landing kinetics during a range of typical lower limb plyometric exercises performed on land and in water.

Study Design: Crossover design.

Methods: Eighteen male participants performed ankle hops, tuck jumps, a countermovement jump, a single-leg vertical jump, and a drop jump from 30 cm in a biomechanics laboratory and in a swimming pool. Land and underwater force plates (Kistler) were used to obtain peak impact force, impulse, rate of force development, and time to reach peak force for the landing phase of each jump.

Results: Significant reductions were observed in peak impact forces (33%-54%), impulse (19%-54%), and rate of force development (33%-62%) in water compared with land for the majority of exercises in this study ($P < 0.05$).

Conclusions: The level of force reduction varies with landing technique, water depth, and participant height and body composition.

Clinical Relevance: This information can be used to reintroduce athletes to the demands of plyometric exercises after injury.

Keywords: aquatic; landing kinetics; jumping; ground reaction force; injury

Lower extremity plyometric exercises are commonly used by athletes to develop explosive speed, strength, and power.[3] They involve stretch-shortening cycle activity, where eccentric muscle contraction is quickly followed by concentric contraction of the same muscle (or muscles). During the eccentric phase (prestretch), the musculotendinous unit is stretched, which stores elastic energy, and the muscle spindles activate the stretch reflex.[32] Potach and Chu[32] suggested that both these mechanisms are responsible for increased muscle recruitment, which allows force production to be maximized during the concentric action. Plyometric training can enhance jumping performance[22] and improve balance and neuromuscular control during landing.[29,30]

Plyometric drills may include jumps, hops, bounds, or shock drills, which vary in intensity,[26] and training often involves repeated maximum efforts. The eccentric activity and high forces generated in plyometric training are also associated with injuries such as patellar tendinopathy.[6,32] Typically, the intensity of an exercise increases with greater ground reaction force (GRF), when jumping up or down from a higher height, and during single-leg exercises.[7] Consequently, landing impacts, joint reaction forces, eccentric rate of force development (RFD), and muscle activity are important factors in assessing intensity.[8,11,19,20] Only a limited number of studies have compared the intensities of a range of plyometric exercises.[19,20]

The majority of plyometric training sessions take place on land. However, there is increasing interest in aquatic-based exercise because this environment provides both physiological and psychological benefits,[21] has similar performance effects as land-based training,[23,25,33] and may be useful in rehabilitation and injury prevention. The effects of gravity are reduced in water because of buoyancy of the body and the increased

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density of water compared to air.[21] The percentage of weightbearing decreases with greater immersion; an individual standing in water to the level of the xiphoid process will bear approximately 28% to 35% body weight (BW), depending on sex.[36,38] Percentage weightbearing will increase with activity (walking) and increasing speed of movement.[14,21]

Research comparing GRF in water and on land has mainly focused on walking.[1,34] The reduced impact forces in water are due to slower walking speeds and reduction in apparent BW.[1] Jumping is more dynamic, with substantial vertical displacements and movement of the limbs in and above the water. The buoyancy force controls the downward movement of the body, thus reducing impact forces and joint loading while assisting the upward concentric phase of a jump.

Previous studies have highlighted the need for research to examine the landing kinetics of aquatic-based plyometric exercises.[25] To date, 2 studies have shown a reduction in GRF during double-leg and single-leg squat jumps in water compared to land.[4,39] The reduction in impact loading can be used to guide the design of training programs. The aim of this study was to quantify the landing kinetics in a range of plyometric exercises performed on land and in water.

MATERIALS AND METHODS

Experimental Design

A repeated measures crossover design was used to determine landing kinetics during jumping exercises on land and in water. The dependent variables included normalized peak GRF, impulse, RFD, and time to reach peak GRF for the landing phase of each jump.

Participants

Ethical approval was obtained from the University of Tsukuba ethics committee before commencement of this study. Eighteen male national swimmers from the university swimming team volunteered to take part in the study and provided written informed consent before their participation (age, 23 ± 1.9 years; height, 1.76 ± 0.06 m; weight, 71.7 ± 6.9 kg; body fat, 20.8 ± 2.5%). They completed a land-based familiarization session within the week before data collection, during which jumping exercises were demonstrated, teaching points were outlined, and participants practiced the techniques.

Instrumentation

Land testing took place in a biomechanics lab, with room temperature recorded as 30.4°C. All jump landings (land and water) used a piezoelectric force plate (9281E, Kistler, Winterthur, Switzerland) with dimensions of 400 × 600 mm and operating at 2000 Hz. Signals from each force plate sensor were recorded and sent to the force plate amplifier (9865E1Y28, Kistler). These analog voltage signals were converted to digital data with a Powerlab 16/30 ML880 system and Chart 5.5.6 (AD Instruments, Nagoya, Japan).

Kinetic data for the aquatic jumps were obtained with a portable underwater force plate (9253B11, Kistler) operating at 2000 Hz. The force plate was on the floor of the pool, embedded into a specially designed platform to provide a large area of uniform height (Figure 1). Water temperature and water depth were maintained at 27.5°C and 1.3 m. Based on the average height of the participants and anthropometric data provided by Drillis and Contini,[41] this corresponded to a water depth of approximately 3 cm below the xiphoid process when participants were standing upright. Participants stood on a box for drop jumps; therefore, initial water depth was lower.

Testing Procedures

Testing sessions. Testing took place on 2 separate days, with a minimum of 4 days between sessions to avoid fatigue and muscle soreness. Participants completed the land testing first, followed by water testing. The intention was to randomize the order in which testing was completed; however, because of equipment availability, this was not possible. All participants wore swimming shorts and Rykä Hydro Step aqua shoes (Rykä, Aliso Viejo, California) for land and water testing. A general warm-up (jogging, stretching) took place before each session. Plyometric exercises included ankle hops, tuck jumps, a countermovement jump, a single-leg vertical jump in place with the dominant leg, and a drop jump from a height of 30 cm (Table 1). Participants were instructed to maintain hands on hips to control for arm contribution and to jump for maximum height in all exercises. All participants were allowed several practice trials before data were collected for 1 trial (with accurate foot placement and correct technique). All exercises were single-effort jumps, except ankle hops and tuck jumps, where the average of 3 contacts were used for data analysis.

Data analysis. Force-time traces obtained from each jump landing were analyzed with Chart software (AD Instruments). For the drop jump, the second landing after the jump was analyzed. Contact periods were defined by the frames in which force exceeded 10 N. Initial contact on the underwater force plate was more difficult to identify because there was a prolonged and gradual increase in vertical force, followed by a more definite increase (Figure 2). The slope of the force-time trace was calculated for successive data points. A subjectively chosen threshold value of 10 000 newtons (N) was used to identify the point where this substantial increase in force and, hence, landing occurred. This method was accurate to 0.02 seconds when compared to landing identified from video recordings obtained at 50 Hz.

Several measures describe the landings, including peak GRF during landing (normalized to BW), landing impulse, RFD, and time to reach peak GRF. BW was obtained during stance on the force plate before data collection. In water, this value was called *apparent BW* (BW minus the upward effect of buoyancy). All exercises except single-leg vertical jump involved landing on both legs; therefore, GRF was absorbed by both legs. A

Figure 1. Force plate embedded in a platform on the floor of the swimming pool.

Table 1. Plyometric exercises, intensity, and instructions for performance.[a]

Plyometric Exercise	Intensity Level	Description
Ankle hops	Low	Stand with feet shoulder-width apart. Begin with a slight countermovement; hop up with movement primarily at ankle joints; repeat immediately on landing.
Countermovement jumps	Low	Stand with feet shoulder-width apart. Begin with a countermovement; explosively jump up for maximum height.
Tuck jumps	Medium	Stand with feet shoulder-width apart. Begin with a countermovement; explosively jump up, pulling knees to the chest; repeat immediately on landing.
Single-leg vertical jump	High	Stand on 1 leg. Begin with a countermovement; explosively jump up for maximum height.
Drop jump	High	Stand with feet shoulder-width apart on a box 30 cm high. Step off without any upward movement. Upon landing, immediately jump up as high as possible.

[a]Adapted from Potach and Chu.[32]

rough estimation of load absorbed by each leg (assuming equal distribution between the legs) can be obtained by dividing the GRF by 2. Landing impulse was obtained by integrating the normalized force-time curve from initial contact on landing until vertical force returned to BW. RFD was calculated as peak normalized GRF, divided by time from initial landing to this peak.

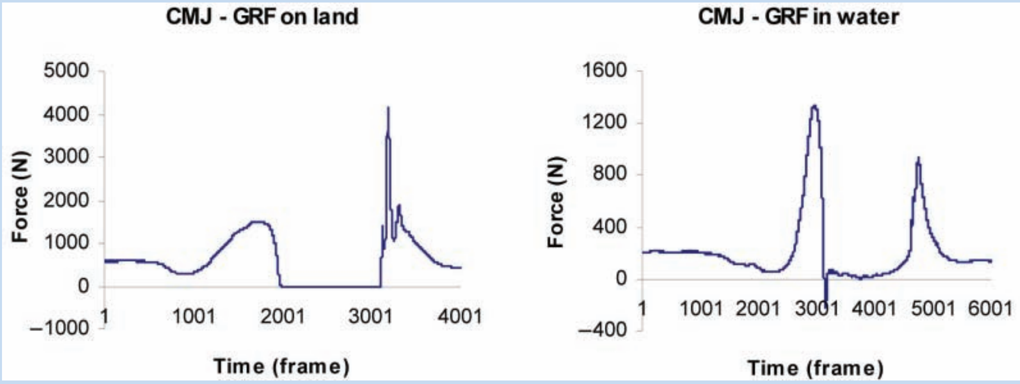

Figure 2. Force-time trace when performing a countermovement jump on land and in water.

Table 2. Peak ground reaction force during landing, normalized to body weight: Mean ± SD.

	Land	Water	Difference, % (Range)	Statistical Result
Ankle hops	5.50 ± 0.94	3.68 ± 0.58*	↓ 33 (19-51)	$P < 0.01$, $d = 2.33$
Tuck jumps	5.00 ± 1.06	2.47 ± 0.59*	↓ 51 (24-66)	$P < 0.01$, $d = 3.28$
Countermovement jump	6.77 ± 1.40	4.04 ± 1.52*	↓ 40 (7-77)	$P < 0.01$, $d = 1.87$
Single-leg vertical jump	4.32 ± 0.55	1.99 ± 0.54*	↓ 54 (25-83)	$P < 0.01$, $d = 4.25$
Drop jump	6.57 ± 1.40	4.05 ± 1.02*	↓ 38 (-12-57)	$P < 0.01$, $d = 2.06$

*Significant difference between land and water conditions ($P < 0.05$).

Statistical analysis. Statistical analysis used PASW Statistics 17. data were checked for skewness and kurtosis while normality was assessed using the Shapiro-Wilks test. Data that violated these assumptions were transformed using square root and log transformations. Data for each exercise were then analyzed using separate repeated measures analyses of variance with 1 within-subjects factor (condition: 2 levels, land and water). Significance level was set at $P < 0.05$. Effect sizes (Cohen's *d*) were calculated with the following formula: effect size = $(\mu_1 - \mu_2) / SD_{pooled}$, where μ_1 and μ_2 represent the means in each condition and where SD_{pooled} was calculated as $\sqrt{[(SD_1^2 + SD_2^2)/2]}$. Interpretation of effect sizes was based on Hopkins criteria, where 0.2, 0.6, 1.2, and > 2.0 represented small, medium, large, and very large effect sizes, respectively.[16]

Data that remained in violation of the normality assumptions after transformation were analyzed using nonparametric statistics. A Wilcoxon signed-rank test was carried out for landing impulse during countermovement jump and drop jump landings and for RFD and time to peak GRF during tuck jumps. Effect sizes were calculated as $r = z / \sqrt{N}$, where z represents the z score from the PASW output and where N represents the number of observations.[10,35]

RESULTS

Peak impact forces on land varied from 4.32 to 6.77 BW, whereas aquatic values varied from 1.99 to 4.05 BW (Table 2). These represented significant reductions in water (33%-54%) with large or very large effect sizes ($P < 0.05$, $d \geq 1.87$). Estimated GRF on each leg was 2.50 to 4.32 BW on land and 1.24 to 2.02 BW in water (Figure 3). On land, there were clear differences in GRF among exercises, with the highest value observed for single-leg vertical jump. However, during aquatic jumps, GRF was almost identical for all exercises except tuck jumps (the lowest).

Impulse was significantly reduced (19%-54%) in water for all exercises ($P < 0.05$) (Table 3). Effect sizes were large or very large for all exercises except countermovement jump and drop jump, which had moderate effect sizes. Variation in responses was evident in 3 exercises (ankle hops, countermovement jump, drop jump) with one participant displaying increased landing impulse.

RFD was significantly reduced (33%-62%) in water for ankle hops, tuck jumps, and the countermovement jump (Table 4). Effect sizes were large for the countermovement jump and moderate for ankle hops and tuck jumps.

Table 3. Landing impulses, N per second: Mean ± SD.

	Land	Water	Difference, % (Range)	Statistical Result
Ankle hop	273 ± 33	224 ± 47*	↓ 19 (–21, 49)	$P < 0.01$, $d = 1.21$
Tuck jump	339 ± 32	245 ± 32*	↓ 29 (11, 45)	$P < 0.01$, $d = 2.97$
Countermovement jump	215 ± 32	143 ± 37*	↓ 34 (–20, 69)	$P < 0.01$, $r = 0.87$
Single-leg vertical jump	161 ± 20	75 ± 29*	↓ 54 (25, 95)	$P < 0.01$, $d = 3.48$
Drop jump	195 ± 24	134 ± 24*	↓ 30 (–10, 49)	$P < 0.01$, $r = 0.86$

*Significant difference between land and water conditions ($P < 0.05$).

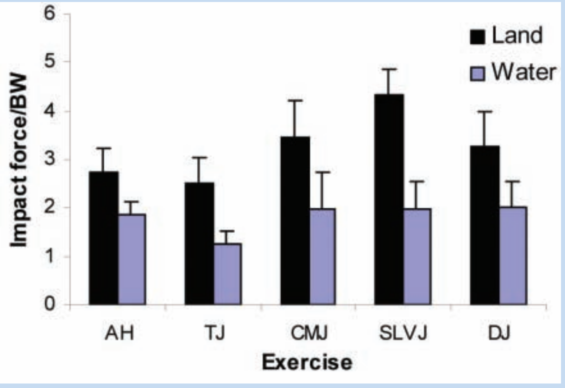

Figure 3. Estimated normalized peak ground reaction force absorbed on each leg (mean ± standard deviation).

Peak GRF occurred significantly later in tuck jumps and countermovement jump but earlier in single-leg vertical jump when jumping in water (Table 5). Effect sizes were moderate for tuck jumps and the countermovement jump and large for the single-leg vertical jump.

DISCUSSION

When landing from plyometric jumps, the body is exposed to high-impact loading, which leads to compression of the spine[12] and lower extremities. This study confirmed that peak GRF and impulse were significantly reduced (33%-54% and 19%-54%, respectively) when performing these jumping exercises in water. This is consistent with previous research that found reductions of 45% and 59% in peak GRF during single- and double-leg squat jumps in water at the level of the xiphoid process.[4,39]

During impact activities, the body is exposed to forces that may have passive and active components. Passive impact forces occur quickly, within the first 10 milliseconds during jump landings.[17] The muscles of the lower extremity need approximately 50 to 75 milliseconds to respond to the landing stimulus and absorb the energy associated with impact; therefore, passive forces are not under neuromuscular control. High-magnitude impact forces and high rates of loading have been linked to injury.[9,18] Active forces occur over a longer period and represent the role of the muscles in force development.[31]

In this study, peak landing GRF occurred after 50 milliseconds in all exercises except the single-leg vertical jump in water; it also occurred significantly later in tuck jumps and the countermovement jump in water compared to on land. In addition, RFD was significantly reduced in ankle hops, tuck jumps, and countermovement jump in water. The tuck jump is the only jump where the knees and hips are flexed during the flight phase, thereby requiring extension in preparation for landing. In water, this less streamlined body position increases the lower limb surface area before contact, which increases drag forces as well as encountering buoyancy resistance. Muscle preactivation is also possible during exercises that involve single and repeated impacts[24]; it may have contributed to the reduced impact forces by allowing the neuromuscular system to prepare for landing. Peak GRF occurred quite early during the single-leg vertical jump in water, which differs from previous research.[39] This was unexpected because buoyancy and increased resistance should reduce the speed at which impact forces develop.

Single-leg exercises tend to be sport specific but are high intensity and consequently require a high level of lower limb strength. The estimated loads absorbed on each leg during double-leg exercises on land were less than those observed for the single-leg vertical jump, which supports previous research (R. Jensen et al, 2008).[21] When performed in water, the single-leg vertical jump resulted in similar impact forces as other exercises. The reductions in the majority of landing kinetic measures support the lower impact aquatic environment as being less stressful, thereby suggesting that single-leg exercises may be tolerated in a water training program earlier than in a land-based equivalent.

Table 4. Rate of force development, body weight per second: Mean ± SD.

	Land	Water	Difference, % (Range)	Statistical Result
Ankle hops	81 ± 32	54 ± 24*	↓ 33 (19-51)	$P < 0.01$, $d = 0.96$
Tuck jumps	69 ± 22	26 ± 34*	↓ 62 (24-66)	$P < 0.01$, $r = 0.76$
Countermovement jump	134 ± 48	68 ± 30*	↓ 50 (7-77)	$P < 0.01$, $d = 1.68$
Single-leg vertical jump	88 ± 24	123 ± 88	↑ 26 (25-83)	$P = 0.31$, $d = -0.36$
Drop jump	120 ± 43	101 ± 43	↓ 20 (-12-57)	$P = 0.06$, $d = 0.57$

*Significant difference between land and water conditions ($P < 0.05$).

Table 5. Time to reach peak ground reaction forces, seconds: Mean ± SD.

Exercise	Land	Water	Statistical Result
Ankle hop	0.074 ± 0.017	0.079 ± 0.028	$P = 0.30$, $d = -0.22$
Tuck jump	0.077 ± 0.026	0.201 ± 0.114*;	$P < 0.01$, $r = -0.76$
Countermovement jump	0.054 ± 0.011	0.064 ± 0.013*	$P = 0.04$, $d = -0.86$
Single-leg vertical jump	0.051 ± 0.009	0.029 ± 0.021*	$P < 0.01$, $d = 1.54$
Drop jump	0.058 ± 0.012	0.050 ± 0.021	$P = 0.12$, $d = 0.47$

*Significant difference between land and water conditions ($P < 0.05$).

This has implications for how aquatic plyometrics can be used in rehabilitation from injury. Land running (although speed dependent) typically involves peak forces of 2 to 3 BW absorbed on a single leg,[2] which is comparable with forces observed in these water-based exercises. Therefore, aquatic plyometrics represent a logical progression that can be used after running but before reintroducing full-effort land-based plyometrics, which would allow the appropriate movement patterns to be reestablished while using the cushioning properties of water and reducing the risk of aggravating the injury. As plyometric exercises involve repeated landings, the number of foot contacts and sessions should be considered when designing a training program.[34]

GRFs measured during land- and water-based exercises in this study were higher than those obtained for similar exercises in previous studies (R. Jensen et al, unpublished data, 2008).[20,40,41] Despite clear reductions in peak GRF, impulse, and RFD in most aquatic plyometric exercises, the level of reduction showed substantial individual variation, partly attributed to water depth, participant height, body composition, and landing techniques. Koury[22] and Miller[27] recommended water of waist height for aquatic plyometrics, suggesting that deeper water may impair control and coordination, making it more difficult to maintain stability in an upright position, decreasing the stretch-shortening cycle reaction time, and increasing drag due to arm swing through the water. Existing research on water-based plyometric programs have used approximate water depths of chest,[24,28,34] waist,[26,28,29] and knee levels.[38] In this study, water depth was fixed at 1.3 m, which reduced the selected kinetic measures by as much as 62% of that typically experienced during land-based plyometrics.

Previous studies used participants with plyometric experience.[4,20,40,41] Given the inexperience of the participants in the current study, variation in jumping and landing strategies was expected. Roesler et al[35] found that positioning the limbs above water during walking affected vertical GRF. Therefore, arm position was standardized in this study (on hips). Landing technique (eg, rearfoot, forefoot, or preferred) can affect joint kinematics,[5] and it may also alter loading. Stiff landings have less joint flexion and typically present high RFD, which is thought to place the individual at greater risk of injury.[11] Training that focuses on correct neuromuscular control and appropriate sagittal and frontal plane alignment are important factors in reducing injury risk[5,15] and can decrease landing forces.[15] Given the kinetic and kinematic differences consistently observed between men and women during landing tasks,[13] it would be interesting to examine potential sex differences between land- and water-based plyometrics.

CONCLUSIONS

Aquatic plyometric exercises are associated with reductions of up to 62% in peak impact forces, impulse, and RFD compared with their land-based equivalents. The level of reduction may be influenced by jumping and landing technique, water depth, and participant height and body composition.

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