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Force during functional exercises on land and in water in older adults with and without knee osteoarthritis: Implications for rehabilitation

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ABSTRACT

Background: Closed kinetic chain and plyometric exercises are commonly used in aquatic rehabilitation because they are believed to reduce joint loading whilst replicating functional tasks. However, the forces and relationship to land-based functional movement is unknown. This study aims to compare vertical ground reaction force during squats, calf raises and jumping in older adults with and without knee osteoarthritis on land and in water.

Methods: Forty one participants (Healthy n = 21; Knee osteoarthritis n = 20; Age 68.5 (4.4) years) completed squats and calf raises at slow, medium and maximal speeds and jumping at maximal speed on land and in waist and chest depth water. Vertical ground reaction force and pain rating was measured in each environment.

Results: Force in all exercises was significantly greater on land than in chest depth water ($p < 0.005$). Peak force was significantly greater at maximal speed compared to slow speed ($p < 0.001$). The pattern of force in squats at slow speed in water was different to on land, with force highest at the start and end of the exercise and decreasing in the central phase. Pain ratings were significantly lower ($p < 0.001$) in water compared to on land in squats.

Conclusions: Closed kinetic chain exercises offer inherently different loading in an aquatic environment. Body weight squats and calf raises in water could be defined as either neuromotor or low load, high velocity training. Maximal speed exercise in water produces higher relative load compared to slow speed and minimal pain providing an opportunity for clinicians to use greater speed to address power deficits.

1. Introduction

Current clinical guidelines for managing knee osteoarthritis include exercise as a fundamental component [1–4]. Various types of exercise interventions are effective in improving pain and function for people with knee osteoarthritis [5,6]. Aquatic exercise is

Abbreviations: CKC, Closed kinetic chain; GRF, Ground reaction force; HA, Healthy older adult participants; KnOA, Older adults with knee osteoarthritis; WBB, Nintendo Wii Balance Board.

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highly recommended as an environment to carry out rehabilitation for this condition [4]. Aquatic exercise is equally as effective as land-based exercise in improving quality of life, function or pain for people with knee osteoarthritis [7–10]. Primarily the value of the aquatic environment for rehabilitation is the reduced load enabling a safe and successful exercise option for people with pain and weakness [8]. Individuals performing exercise in water experience the upthrust force of buoyancy, reducing weight bearing load in standing in water relative to the volume of water displaced and the depth of immersion [11]. Specifically, reduced loading due to buoyancy may allow individuals with pain or weakness to perform more challenging functional tasks in the water, such as single leg exercises which would not be possible on land [12].

Drag force is also influential during aquatic exercise, and increases with greater speed or increases in the projected surface area of the moving part of the body [11]. In water, greater speed, along with using equipment with a larger surface area, significantly increases load in open chain exercises such as knee extension in water [13,14]. Although equipment may not always be available, clinicians can modify instructions regarding speed during exercises to alter resistance. Speed and subsequent drag force are critically important to consider in aquatic exercise prescription as they both change the load and the movement task specificity relative to land-based function [12]. The velocity of muscle contraction is an important factor in specific training and performance adaptations [15,16] and requires greater consideration in aquatic rehabilitation.

Aquatic open chain knee exercise force in water is quantified [17,18] but little is understood about load in closed kinetic chain (CKC) exercises. Land-based exercises are used in rehabilitation to train movement patterns mirroring daily tasks and address sensorimotor deficits and functional instability in knee osteoarthritis [19,20]. CKC exercises are commonly prescribed in musculoskeletal aquatic rehabilitation programmes [21] but the relationship to the specificity of land-based CKC exercises is unknown. Preliminary evidence confirms reduced hip and knee joint forces when performing squats in water compared to on land [14] but no ground reaction force quantification for squats or other CKC exercises such as calf raises in water exists. The influence of speed on forces in CKC exercises in water is also unknown.

In addition to CKC exercises, plyometric exercises such as jumping are also used in aquatic rehabilitation programmes for older adults [22–26] and in people with knee osteoarthritis [9,27]. Although explosive exercise in older adults has value in improving both strength and functional performance [28], plyometric exercise is underutilized in musculoskeletal aquatic rehabilitation [29]. There is growing interest in the feasibility and safety of high velocity power training for people with knee osteoarthritis due to the link with improvements in function [30,31] and potential to reduce falls by enhancing their capacity to perform rapid, high force contractions [32]. This high velocity training is performed in open kinetic chain non-weight bearing positions of the knee joint [30–32] as pain with weight-bearing load is often a feature of knee osteoarthritis [33]. Explosive weight bearing exercises such as jumping may offer another opportunity for power training for people with knee osteoarthritis in more functional positions but with lower loads compared to on land. The kinetics of jumping in water is quantified in young adults [29,34–37] but the potential benefits of similar propulsive forces but lower impact forces in water compared to on land are not confirmed in older adults or people with musculoskeletal conditions. Additionally, the tolerance or pain associated with these types of exercises is also unknown.

This study aims to compare the peak vertical ground reaction force (GRF) during bilateral and unilateral squats and calf raises in older adults with and without knee osteoarthritis at varying speeds on land compared to in water. Jumping at maximal speed in both groups will also be investigated on land compared to in water. Due to the parameters of buoyancy being directly related to the volume of the body under the water and the subsequent influencing on relative weight-bearing, the study aimed to review the pattern of GRF throughout the exercises. For the participants with knee osteoarthritis, pain with exercises on land will also be compared to the same exercise in water.

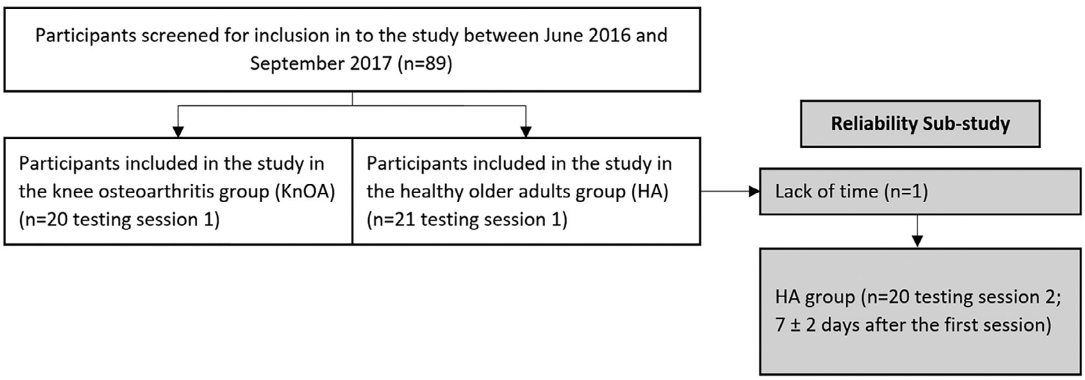

Figure 1. Flow chart of inclusion in the study.

2. Methods

2.1. Participants

A convenience sample of two groups over 60 years of age were recruited using information flyers at local leisure centres, community centres and hospitals in Melbourne, Australia including, healthy older adults (HA) and older adults with knee osteoarthritis (KnOA).

Individuals telephoned research staff to express interest in the study and were screened using the inclusion and exclusion criteria. The inclusion criteria for all participants were i) over 60 years of age; ii) no neuromotor impairments; iii) no history of falls; iv) no lower limb joint replacement surgery and v) no back, hip or ankle pain in activities of daily living. The HA group had no reported knee pain and the KnOA group fulfilled the National Institute for Health and Care Excellence (NICE) criteria [1] for the diagnosis which included knee pain with movement and morning stiffness of less than 30 min. NICE criteria for diagnosis of knee osteoarthritis [1] do not require an X-ray therefore this information was not collected in this study. A description of radiographical severity is not able to be provided for these participants but a minimum of subjective pain of three out of 10 during a functional activity was an inclusion criterion for the KnOA group. The flow of participants in the study is detailed in Figure 1. Participants were excluded if they demonstrated i) limitations to exercise and ii) contraindications to immersion and exercise in a hydrotherapy pool [38].

The power calculation was based on a more conservative estimate of large effect sizes in vertical GRF on land and in water based on the large effect size shown in gait in older adults [39]; Cohen's $d = 0.9$, statistical power $= 0.8$ and $p = 0.05$, requiring a minimum of 21 participants per group for the cross-sectional study.

All participants provided written informed consent prior to any data collection and the relevant Human Research Ethics Committee approved the study (St Vincent's Hospital Melbourne 060/15).

2.2. Procedure

The study utilized a cross-sectional, observational design (with an additional test–retest reliability component for the HA group only). Participants in both groups were assessed by performing a series of four exercises at different speeds and jumping at maximal speed on land and in water. Participants were asked not to complete any resistance training for 48 h prior to any testing sessions to limit the influence of prior exercise on pain, fatigue and performance. Height and weight were recorded prior to testing. All participants were interviewed on their medical and exercise history.

Testing was completed first on land and then at waist depth (to the level of the anterior superior iliac spine or up to five centimetres deeper) and lastly at chest depth (xiphisternal depth or up to five centimetres deeper) in a hydrotherapy pool (temperature 34 °C) (Figure 2). The environmental conditions were not randomised due to safety concerns with participants and equipment being tested on land after being in a wet environment. Therefore exercise on land was tested first, followed by water depth at waist and then chest level with the practice effect limited by the change in environment.

2.3. Equipment

The kinetic outcome examined was peak vertical GRF during each exercise. Vertical GRF data were captured using two modified Nintendo Wii Balance Boards (WBB) (Nintendo, Kyoto, Japan). The bilateral exercises utilized the two WBBs, one for each leg with the outcome the sum of the GRF and the unilateral exercises involved standing on one WBB with only force from this board used in analysis. The WBB has previously been found to be reliable and valid for assessment of static and dynamic standing balance [40,41,48]. Both WBBs were modified with wet area silicone (Selleys, Padstow, Australia) on each of the four load cells and cabling with the batteries and circuit board removed from the main casing and reconnected to longer cabling to allow the batteries and circuit board to be out of the water during the testing in the pool. Each WBB was connected by Bluetooth to a laptop computer using custom software (LabVIEW, National Instruments, Austin, U.S.A.). Calibration was performed in each environment for every testing session by placing four known loads (dumbbells) on both WBBs sequentially [37]. The recorded values were then compared to the known values and a linear regression performed to create the scale and offset factors. The formula for determining the force of the dumbbells underwater used the principle: an object's loss of weight in water is equal to the weight of the volume of water it displaces [11]. The volume of one gram of water occupies a volume of exactly one millilitre at four degrees Celsius when water is at its greatest density and increasing the temperature will increase the volume of the same weight of water [11]. This procedure was carried out in water at 34 °C, the same as the temperature of the hydrotherapy pool during the calibration procedures. The scales used offered a capacity of 220 kg and a resolution of 0.02 kg (HW-PW200, A&D Weighing, Adelaide, Australia). The calculated relative loss of weight of the dumbbell in water was equal to the weight of a container full of water with the dumbbell immersed in it, subtracted from the combined weight of the same container full of water and the dumbbell weighed separately.

To ensure the validity of the modified WBBs, we performed reliability assessment and criterion reference validation in water and on land (Supplementary materials 1 and 2). Reliability assessment consisted of a subset of the HA group ($n = 20$, age 67.85 (4.24)), tested in second session, 7 ± 2 days apart using exactly the same methodology and exercises both on land and in water. Test–retest reliability for the peak vertical GRF during all exercises was good to excellent (Supplementary material 1: Spearman's correlation coefficient 0.83–0.99 land; 0.77–0.93 waist-depth; 0.62–0.98 chest depth). Criterion reference validation consisted of

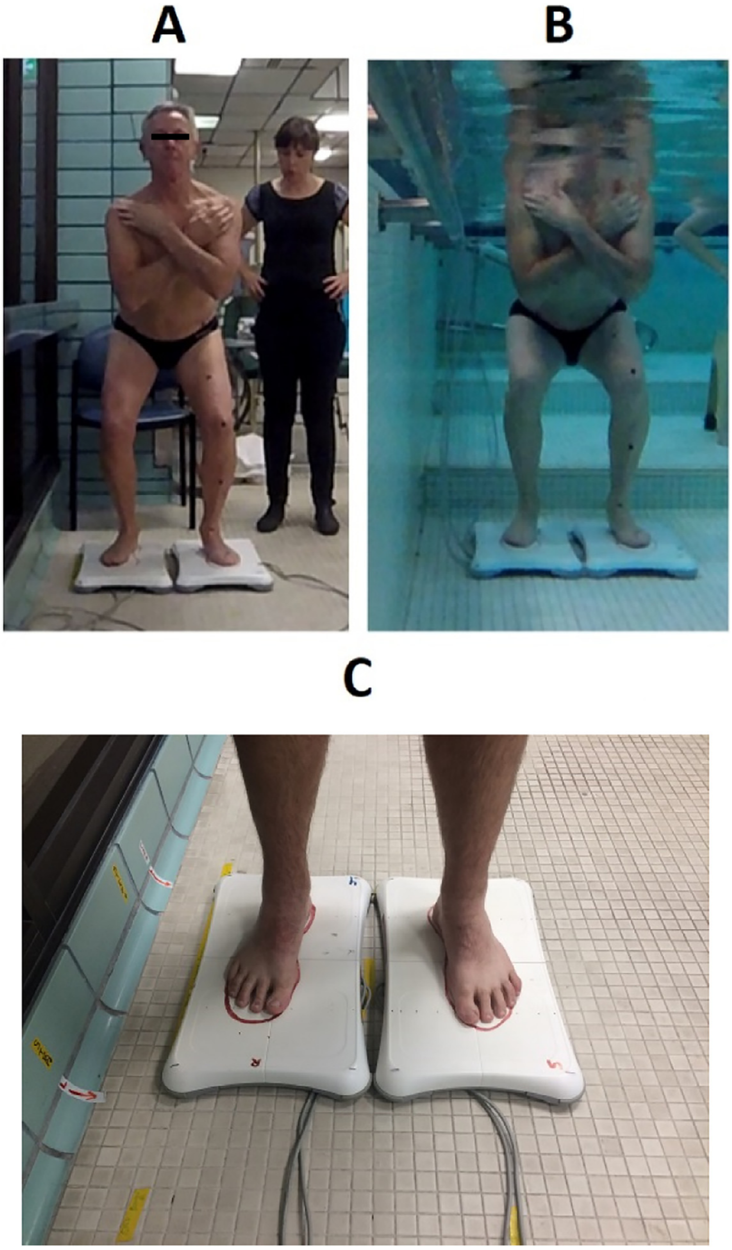

Figure 2. Testing position on land (A), in the water (B) and a close-up of foot placement on the two WBB (C). Note that in B the pool had a stepped design, with the WBB moved to the correct step height depending on the participant's height and the depth of immersion required.

comparing static and dynamic force values obtained from the WBBs with those obtained from a load cell (Meltrons MT501 S-type; 250 kg, Smithfield, Australia). Static and dynamic force values compared favourably to the load cell with low mean absolute error and negligible visual differences between traces (Supplementary material 2). This was reinforced by previous research findings that vertical ground reaction force data from underwater force platforms is reliable [42].

Secondary outcomes included subjective reporting of pain for KnOA participants after each type of exercise determined using the valid Verbal Rating Scale [43], preferred by older adults [44]. The six-point scale included no pain, mild pain, moderate pain, severe pain, very severe pain and the worst imaginable pain. Participants also rated pain before each new environment to determine if a cumulative increase in pain during the testing session occurred. All conditions for all participants started testing with no pain except for one participant who started chest depth testing reporting mild pain.

2.4. Exercises

Lower limb CKC exercises were chosen based on commonly used exercises in musculoskeletal aquatic rehabilitation [21]. They consisted of double and single leg trials with speeds defined in previous literature covering slow (30°/s) [45], medium (90°/s) [46] and fastest possible. Unilateral exercises were tested on the left leg for the HA participants and on the symptomatic leg for the participants with knee osteoarthritis. For single leg exercises the participant utilized light touch upper limb contact with the contralateral side on a rail for balance with fingertips only.

The exercises were tested in the following order: bilateral and unilateral leg squats, bilateral and unilateral leg calf raises and a counter-movement jump. Squats and calf raises were tested at slow (three seconds in each direction of movement), medium (one second in each direction of movement) and fastest possible speeds. Instructions for squats were to flex the knee to as close to 90° as control of the movement allowed. Squat depth and calf-raise height were not standardized, and were based on the participant's comfort and control as per clinical practice and depth of the squat will have varied due to a range of factors including strength, pain and confidence with movement. This ensured that although the angular joint velocity of each squat or calf raise was not exactly the same between participants due to the varied range of movement, the test time of the task was the same. Instructions for counter-movement jumps directed participants to squat with knee flexion to as close to 90° as comfort and control allowed and then rapidly push to extend the legs and jump as high as possible. Prior to testing, all exercises were demonstrated first then practiced once. A metronome provided an audible feedback for the timing of the exercise. Two repetitions of each exercise were completed. If the participant used more than fingertip rail support or lost their balance in any of the exercises the trial was discarded and repeated. If a participant perceived they could not complete the movement due to lack of control or unreasonable pain, they could decline to perform the exercise.

2.5. Data analysis

Both WBBs sampled at 40 Hz and were filtered using a 4th order Butterworth zero-phase shift filter with a lowpass cut-off frequency of 20 Hz [47]. The mean peak force for the two repetitions of each exercise in each environment at each speed was determined and converted to a figure relative to their land body weight (Excel, Microsoft). Any trials indicating measurement or equipment error, as indicated by large spikes in the visual inspection of the data were discarded. Additionally, if an issue with the calibration file and scale factor created an R^2 value of less than 0.95 testing in that environment was discarded. The data files for some of the trials were blank, indicating operator error during testing or failure of the Bluetooth system to transmit the data. In these circumstances, participant data did not contribute to the analysis. This represented approximately 10% of trials.

2.6. Statistical analysis

Descriptive statistics were calculated for participant characteristics. To address the first hypothesis related to differences in force, the pattern of force throughout each exercise was examined and described qualitatively. Additionally, the peak force for each exercise in each environmental condition (at the same speed) was assessed. Outliers were checked using box plots and assumptions of normality of each distribution and the variance of homogeneity were tested with Shapiro Wilk's test and the Levine test, respectively. As the majority of data violated one or all of these assumptions, median and interquartile ranges were used to describe the peak force for each exercise. Non-parametric tests (Friedman test; repeated measures) were used to test the first hypothesis comparing peak forces between environmental conditions at the same speed (three environmental conditions, one

Table 1
Descriptive characteristics of participants: mean (SD) unless stated otherwise.

	Healthy older adults	Older adults with knee osteoarthritis
n	21	20
Female	11	8
Age	67.71 (4.19)	69.35 (4.65)
Height (m)	1.67 (0.09)	1.719 (0.08)
Weight (kg)	73.52 (14.91)	82.54 (16.88)
BMI	26.25 (4.15)	27.77 (4.37)
Physical activity (walking) hours/week	3.512 (6.37)	2.54 (2.55)
Regular land exercise (%)	76	80
Hours land exercise/week	3.726 (3.40)	2.445 (3.23)
Hours land resistance training/week	0.286 (0.62)	0.105 (0.32)
Regular aquatic exercise (%)	24	30
Hours aquatic exercise/week	1.19 (3.39)	0.75 (1.37)
Cardiovascular comorbidity (%)	33	40
Respiratory comorbidity (%)	5	15

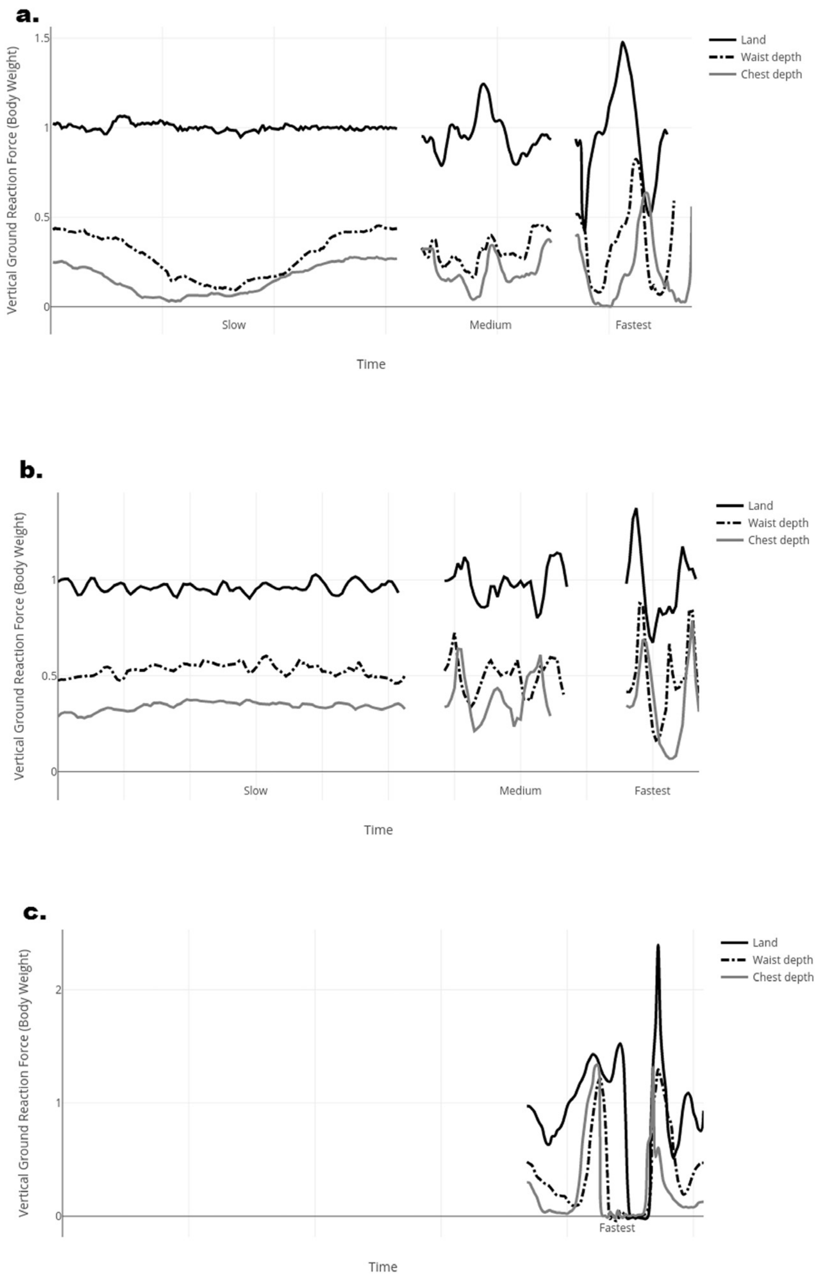

Figure 3. Force–time curve. a. Squat: During the squat the pattern of force was similar across conditions: the force associated with quiet standing initially demonstrated an unloading phase and then increased to a peak in the central part of the movement. The most notable exception was when a squat was performed at slow speed in water, with the peak of the force absent and replaced by a decrease in force from quiet standing. b. Calf raise: Calf raises at medium and fast speed in both groups on land and in water demonstrate two peaks, one in the first phase of the exercise corresponding to elevation of the body and one corresponding to the second lowering phase of the exercise. In contrast, at slow speed in water, only one peak in force was present with a more gradual increase in load to a flattened central peak as the body rises out of the water. c. Counter-movement Jump: For a counter-movement jump, there were two peaks in the force–time curve which approximated the propulsive phase and the landing phase in all environmental conditions. The only noticeable, common difference between the environments was that the magnitude of the impact peak force was at least 0.5 times body weight load greater than the propulsive peak on land, but in water this difference was absent (Table 2).

speed); the second hypothesis comparing peak force with increasing speed in each environmental condition (three speeds, one environmental condition) and the third hypothesis comparing pain ratings between exercises on land compared to the same exercise in water was in the KnOA group (three environmental conditions, one speed). Pairwise comparisons using the Wilcoxon signed-rank test were used as appropriate. There was no correction for multiple tests applied which may have led to false positives but was appropriate as there are other issues with adjusting for multiple tests [44]. Additionally, standardized mean difference (Hedges' g) was calculated (Review Manager. Version 5.3; Copenhagen, Denmark) comparing force data in each condition to allow a scale free comparison [49] to previously published data of magnitude of effects [12]. Effect size estimates were interpreted as small (0.2), medium (0.5) or large (0.8) [49]. Significance was set at $p < 0.05$ for all tests. Statistical analysis was performed using SPSS® software (Version 24, IBM, Armonk, NY).

3. Results

Forty one participants completed the study (HA $n = 21$; KnOA $n = 20$) (Table 1). There were no adverse events during the testing. Two KnOA participants were unable to complete the calf raises due to loss of balance and another declined to complete the jumping due to lack of lower limb control and poor balance.

3.1. Force during exercises

Body weight (BW) load in quiet standing at the start and end of each exercise was approximately 1.0 on land, 0.44–0.53 BW at waist depth and 0.30–0.38 BW at chest depth.

3.1.1. Pattern of force

The force–time curves were similar for all participants regardless of group (HA or KnOA), and although exact timing of change in force throughout the exercise cannot be estimated, the pattern of change was the same for all participants therefore description of the force profiles will include all participants. The force–time curves of a typical participant are described qualitatively and illustrated graphically (in Figure 3).

3.2. Differences in peak force across environmental conditions at the same speed

Force in all exercises was significantly different ($p \leq 0.001$) between environmental conditions (Table 2).

Post hoc analysis revealed the majority of exercises on land having the greatest peak force, followed by exercises in waist depth water which were in turn greater than exercises in chest depth water. The few exceptions to this finding are detailed further in the next paragraph. Peak force was significantly greater ($p \leq 0.005$) on land when compared to chest depth water in all exercises in both groups.

In contrast to the consistent finding of typically greater force in waist depth water compared to chest depth water, only exercises completed at fastest possible speeds showed no difference between peak force at waist and chest depths. These exercises included fastest possible bilateral squats (both groups) ($p > 0.059$), fastest possible bilateral calf raise propulsive force (HA) ($p = 0.100$), bilateral calf raise impact force (KnOA) ($p = 0.480$) and the propulsive peak force in jumping (KnOA). There was only one exercise where significantly greater peak force was demonstrated in chest deep water compared to waist deep water and this was in the propulsive phase of jumping in the HC group ($p = 0.005$).

3.3. Differences in peak force with changing speed within the same environmental condition

Effect of changing speed on peak force in all exercises was significantly different ($p < 0.001$) for all environmental conditions. Post-hoc testing revealed that when performed at fastest speed, peak force was significantly greater than for slow speed for all exercises in both groups. Similarly, when performed at fastest speed, peak force was significantly greater than for medium speed for all exercises except for unilateral squats on land in the KnOA group. Non-significant differences in peak forces between slow and medium speeds occurred in the majority of exercises at waist depth (Table 3).

3.4. Pain ratings

Pain ratings were significantly lower ($p < 0.001$) in water compared to on land in bilateral and unilateral squats at all speeds (Figure 4). Post hoc testing revealed pain ratings significantly lower in both waist and chest depth water compared to on land for squats at all speeds except unilateral squat at fastest speed, which was only significantly lower in chest depth immersion compared to on land. Similarly, pain ratings were significantly lower ($p < 0.001$) in water compared to on land in unilateral calf raises at slow speeds for significantly lower pain exercising in chest depth water compared to on land. Jumping in water was pain free in participants, both on land and in water.

4. Discussion

This study indicates that closed kinetic chain exercises have greater ground reaction forces on land compared to in water in older adults with and without knee osteoarthritis. Additionally, force increases as speed increases in all environmental conditions. Therefore, our findings suggest that CKC exercise at particular speeds creates different loading, leading to different resistance and therefore altered subsequent stimulus on lower limb musculature that is unique to each environment. When prescribing functional exercises, clinical reasoning on choice of therapy setting and instructions on speed, as well as quality of movement, treatment goals and individual preferences needs to be considered. Effective application of lower load exercises in water, particularly

Table 2
Peak force for squats, calf raises and jumping in all environmental conditions at the same speed.

Exercise	Speed	n	Force (BW) Median (IQR)			Standardized mean difference		
			Land	Waist	Chest	Land–waist	Land–chest	Waist–chest
Healthy older adults								
Bilateral squat	Slow	12	1.09 (0.04)	0.53 (0.06)	0.38 (0.08)	11.29*	9.37*	2.02*
	Medium	16	1.23 (0.10)	0.56 (0.08)	0.41 (0.12)	10.25*	10.44*	1.68*
	Fastest	16	1.5 (0.11)	0.67 (0.18)	0.63 (0.24)	5.60*	5.81*	0.41
Unilateral squat	Slow	18	1.05 (0.12)	0.49 (0.10)	0.32 (0.10)	7.08*	9.48*	2.40*
	Medium	16	1.17 (0.14)	0.53 (0.09)	0.39 (0.05)	6.51*	7.89*	1.15*
	Fastest	17	1.28 (0.18)	0.65 (0.16)	0.55 (0.20)	5.34*	4.55*	0.16*
Bilateral calf raise	Slow	15	1.09 (0.06)	0.62 (0.08)	0.45 (0.08)	6.61*	12.54*	2.79*
	Medium (P1)	15	1.14 (0.08)	0.68 (0.07)	0.51 (0.10)	6.73*	8.21*	1.96*
	Medium (P2)	16	1.16 (0.09)	0.67 (0.09)	0.51 (0.11)	5.58*	8.21*	1.95*
	Fastest (P1)	15	1.41 (0.14)	0.96 (0.17)	0.77 (0.10)	3.54*	5.16*	0.77
	Fastest (P2)	15	1.29 (0.25)	0.88 (0.22)	0.81 (0.19)	2.32*	3.07*	0.77*
Unilateral calf raise	Slow	17	1.03 (0.12)	0.58 (0.09)	0.40 (0.11)	5.86*	7.93*	2.38*
	Medium (P1)	16	1.14 (0.15)	0.66 (0.11)	0.47 (0.15)	4.95*	6.47*	1.85*
	Medium (P2)	16	1.11 (0.17)	0.62 (0.07)	0.44 (0.12)	5.42*	7.03*	2.35*
	Fastest (P1)	17	1.26 (0.11)	0.86 (0.24)	0.69 (0.20)	2.73*	3.70*	1.01*
	Fastest (P2)	17	1.30 (0.09)	0.81 (0.19)	0.60 (0.15)	3.40*	4.65*	1.23*
Jump propulsion	Fastest	16	1.83 (0.20)	0.96 (0.17)	1.27 (0.20)	5.76*	3.00*	−2.40*
Jump landing	Fastest	16	2.38 (0.73)	0.88 (0.22)	1.17 (0.28)	5.23*	3.27*	−1.25*
Older adults with knee osteoarthritis								
Double leg squat	Slow	13	1.06 (0.06)	0.51 (0.11)	0.32 (0.07)	7.83*	12.2*	2.35*
	Medium	15	1.20 (0.13)	0.54 (0.11)	0.39 (0.14)	9.49*	10.48*	1.70*
	Fastest	14	1.41 (0.18)	0.62 (0.13)	0.55 (0.17)	5.97*	6.04*	0.84
Single leg squat	Slow	14	1.01 (0.05)	0.44 (0.12)	0.30 (0.07)	8.93*	14.06*	2.76*
	Medium	16	1.08 (0.07)	0.47 (0.10)	0.35 (0.07)	7.76*	11.96*	1.93*
	Fastest	13	1.16 (0.12)	0.56 (0.09)	0.44 (0.09)	6.68*	9.36*	1.47*
Bilateral calf raise	Slow	15	1.08 (0.08)	0.57 (0.09)	0.43 (0.06)	8.29*	12.53*	2.55*
	Medium (P1)	15	1.07 (0.08)	0.63 (0.13)	0.42 (0.10)	6.59*	9.22*	2.2*
	Medium (P2)	15	1.11 (0.13)	0.61 (0.13)	0.43 (0.14)	5.25*	5.94*	1.63*
	Fastest (P1)	9	1.34 (0.21)	0.86 (0.16)	0.65 (0.19)	2.96*	4.97*	1.30*
	Fastest (P2)	9	1.37 (0.23)	0.80 (0.22)	0.67 (0.22)	2.25*	5.11*	0.98
Unilateral calf raise	Slow	13	1.00 (0.02)	0.51 (0.08)	0.37 (0.05)	7.66*	12.47*	2.42*
	Medium (P1)	14	1.07 (0.05)	0.60 (0.11)	0.44 (011)	6.12*	8.15*	2.23*
	Medium (P2)	14	1.03 (0.08)	0.57 (0.12)	0.42 (0.11)	5.09*	7.60*	1.92*
	Fastest (P1)	15	1.22 (0.13)	0.73 (0.17)	0.58 (0.13)	5.09*	6.72*	1.63*
	Fastest (P2)	15	1.22 (0.09)	0.70 (0.14)	0.53 (0.16)	2.61*	5.82*	1.06*
Jump propulsion	Fastest	15	1.84 (0.31)	1.17 (0.29)	1.19 (0.42)	2.63*	2.36*	−0.12
Jump landing	Fastest	16	2.54 (0.64)	1.45 (0.58)	1.16 (0.26)	2.80*	4.35*	1.40*

P1: Peak 1; P2: Peak 2; BW: body weight. IQR: interquartile range.
* Significant pairwise comparison $p < 0.05$.

related to the role of speed and the aim of increasing strength, needs to be examined further. Importantly, pain is lower in CKC exercise in water compared to on land, and the potential for aquatic exercise at faster speeds to encourage greater loads may be well tolerated by people with knee osteoarthritis. Surprisingly, jumping, with relatively higher loads compared to the other exercises, also had minimal pain both in water and on land. Maximal speed CKC exercise and jumping in water may offer exciting contributions for interventions to improve power and function.

This study confirms significantly lower loads during aquatic exercise compared to exercise on land, and provides more comprehensive information for clinical reasoning in prescribing squats in water. Lower loads and less pain with aquatic squats indicate their potential value for more comfortable weight-bearing exercise. Squats, along with other CKC movements such as lunges, are commonly prescribed neuromuscular exercises used to address coordination and functional performance to improve joint stability in people with knee osteoarthritis [20]. Although improvements in motor control were not assessed in this study, knee pain is one mechanism of inhibition of quadriceps activation in various knee joint pathologies [50]. Further investigation into whether reduced pain with squats in water facilitates more coordinated knee control is warranted as additional advantage may exist with neuromuscular exercise in water in retraining functional movement stability, alignment and control, which is effective in land rehabilitation in reducing pain and disability for people with knee osteoarthritis [20,19]. Further investigation is also required in older adults to determine if reduced GRF with movement on land following plyometric and landing training in water can be achieved as has been demonstrated in younger adults [51]. The magnitude of effect between vertical GRF on land and water is large, which is also shown in previously published studies in walking and stationary running [12]. Whilst there are no other studies investigating GRF in CKC exercise in water, our loads in quiet standing at waist and chest depth are comparable to other research [37,53,54].

Speed can guide aquatic exercise prescription with squats to be specific to particular therapy goals. Previous research suggests that lower limb exercises on land using low load performed at high velocity compared to higher loads has similar improvements

Table 3
Standardized mean difference comparing peak force with changing speed in the same environmental condition (please refer to Table 2 for peak force data).

Exercise	Speed	n	Standardized mean difference		
			Slow–medium	Slow–fastest	Medium–fastest
Healthy older adults					
Bilateral squat	Land	13	−2.68*	−3.96*	−2.39*
	Waist	17	−0.49	−1.65*	−1.38*
	Chest	17	−0.86	−2.25*	−1.71*
Unilateral squat	Land	17	−1.03*	−2.02*	−1.09*
	Waist	21	−0.61*	−0.62*	−0.44*
	Chest	20	−0.83*	−1.92*	−1.27*
Bilateral calf raise	Land	17	−1.28*	−2.86*	−2.19*
	Waist	17	−0.80	−3.09*	−2.43*
	Chest	15	−1.18*	−3.77*	−2.77*
Unilateral calf raise	Land	17	−0.88*	−2.23*	−1.42*
	Waist	19	−1.10*	−2.54*	−1.73*
	Chest	20	−0.91*	−2.56*	−1.76*
Older adults with knee osteoarthritis					
Double leg squat	Land	12	−1.94*	−2.85*	−1.77*
	Waist	19	−0.39	−1.73*	−1.47*
	Chest	16	−0.97*	−2.22*	−1.44*
Single leg squat	Land	12	−1.11*	−2.05*	−0.91
	Waist	18	−0.26	−1.21*	−0.92*
	Chest	20	−1.18*	−2.42*	−1.45*
Bilateral calf raise	Land	11	−0.91*	−3.13*	−1.87*
	Waist	14	−0.65	−1.76*	−1.48*
	Chest	13	−0.66*	−3.05*	−1.86*
Unilateral calf raise	Land	12	−1.00*	−2.67*	−1.62*
	Waist	17	−1.21*	−1.84*	−1.12*
	Chest	15	−1.05*	−2.97*	−1.81*

* Significant pairwise comparison $p < 0.05$.

in power in older adults [55] and in strength, function and pain in people with knee osteoarthritis [31]. Our findings support defining aquatic squats as low load high velocity strength training at the forces produced during fastest possible speeds compared to the forces produced on land. Given that few programmes give instructions to maximise speed with aquatic exercise [29], our findings indicate that low load high velocity resistance training using CKC exercises may hold promise for future aquatic rehabilitation programme planning. In contrast, at slow speeds, our novel finding of different patterns of force in squats in water compared to on land indicates this exercise is unlikely to be effective for strengthening [29]. The lowest force in water is seen during the middle part of the exercise, related to the trunk being lowered into the water, when the knee is likely to be in greatest flexion but with minimal GRF. The important clinical implication for aquatic squats at slow speeds is the lowest knee load occurs in the most flexed position, leading to significantly different task-specificity in quadriceps activation and stimulus than on land. Slow squats in water may be most appropriate for addressing flexibility, functional knee range of movement, coordination or confidence with movement and slow squats will not be appropriate to optimize quadriceps stimulus in flexed positions particularly if the goal in rehabilitation is to improve functional capacity in sit-to-stand on land. At slow speeds with calf raises, this significant off-loading during the exercise is not a consideration as the body is moving out of the water, therefore body weight load and resistance for the exercise are increasing. Clinicians must be challenged to not only consider speed with exercise, but also prescribe it with a particular goal for the exercise in mind.

Lower loading in jumping may have benefits in allowing people with degenerative joint conditions an opportunity to complete power based training in a comfortable environment. Higher loads in chest depth compared to waist depth water in this study may be due to greater surface area of the body under water, and therefore greater drag forces to overcome. Clinically, deeper immersion leading to reduced load cannot be assumed when introducing plyometric exercises, or CKC exercises at fastest speeds, into rehabilitation programmes. Interestingly, few studies specifically use plyometric exercises as an intervention for older adults [22], instead plyometric exercises are most commonly prescribed in the aerobic component of aquatic programmes [23–26]. This may add confusion to clinical reasoning and exercise prescription as if plyometric exercises are only included when prescribing cardiovascular conditioning in aquatic exercise programmes, the potential for this training to improve leg power may not be fully utilized. Unusually with jumping, although the highest loads across all environments were recorded, participants with knee osteoarthritis reported minimal pain. This exercise may indeed be well tolerated in aquatic rehabilitation to improve power, which is related to overall function and mobility in older adults [56]. Similar loading in the propulsive phase of jumping on land and in water in younger adults [34–37], may relate to differences in data analysis, slower maximal speed of the exercise or a greater challenge to balance and stability with this exercise in a novel environment. Consideration that only GRF was measured in this study, not joint force, which should lead to a conservative approach to adding plyometric exercises to aquatic rehabilitation programmes. A prior study reported much higher in vivo hip and knee joint forces during squats and jumping in water in participants using instrumented implants [14] compared to the GRF in our findings. However, direct comparison of forces is not possible due to not only our measurement of GRF versus in vivo force but also the differing normalisation methods. The in vivo

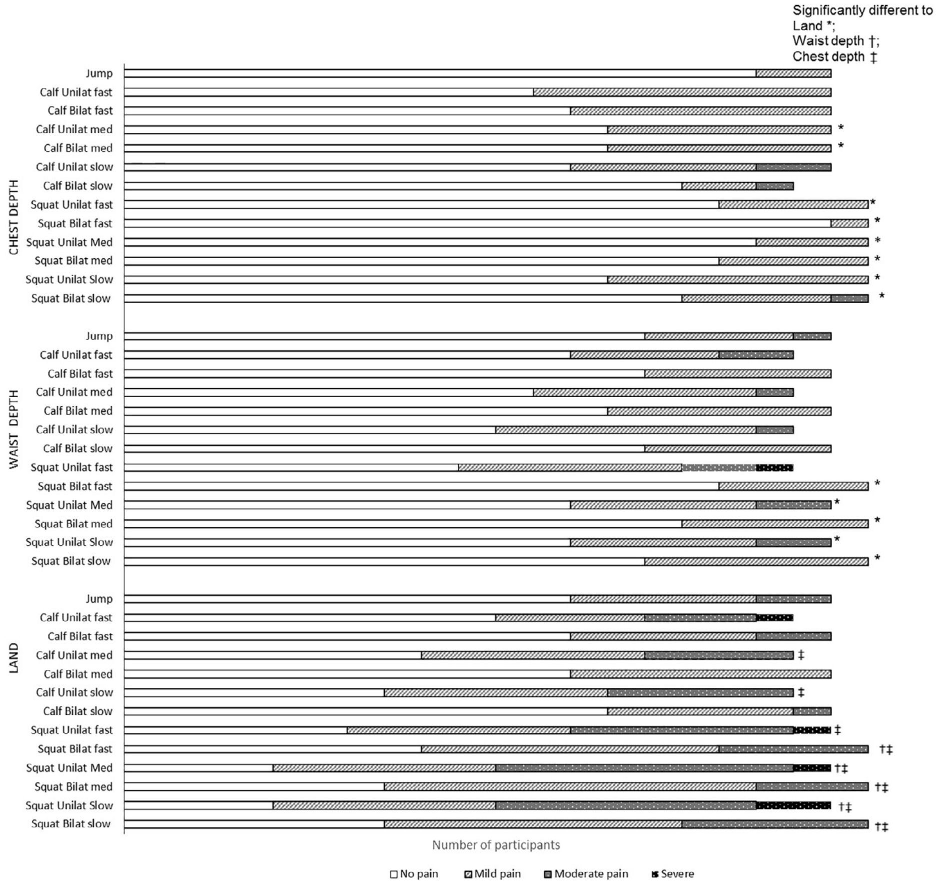

Figure 4. Pain ratings for exercise.

joint force study [14] normalised forces to body weight within the environment, i.e. force when exercising in water was normalised to static standing force in water (with single leg stance in chest deep water equal to approximately 100% of body weight in water) [52] as opposed to normalising force to static standing force on land when exercising in water in this study.

Conclusions and clinical implications from our results must be balanced by the limitations of the study. The depth for the squat and height of the calf raise were not strictly controlled which although is typical of how these movements are performed, we may have missed significant findings. Differences in forces between conditions and speeds were confirmed despite this variability. There was no statistical correction applied for multiple post-hoc testing [44]. Finally, participants with knee osteoarthritis in this study were very active, and although our findings may be generalizable to people following knee arthroscopy or minor knee ligament joint sprains, they may not be generalizable to more sedentary individuals with knee osteoarthritis.

5. Conclusions

In conclusion, this study clarifies some of the differences in force of functional lower limb aquatic exercise which has significant implications for rehabilitation. Squats, calf raises and jumping facilitates greater force on land compared to exercise in water for both healthy older adults and older adults with knee osteoarthritis. Exercises at greater speed demonstrate significantly higher peak force in all environmental conditions. Speed can be easily monitored and prescribed both on land and in water as a means of estimating or modifying load. This can aid in the selection of appropriate types of exercise for therapy goals from flexibility to neuromotor control to low load, high velocity strengthening exercise. Importantly, squats in water are less painful than on land for people with knee osteoarthritis adding utility. Exercise using body weight load in water typically results in GRF that are far lower than the same CKC exercise on land, and therefore may not be sufficient for high intensity strengthening. The tolerance and value of high velocity training, as with plyometric training, require further investigations in older adults with and without musculoskeletal conditions.

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Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.knee.2018.11.003.

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