

TRUNK, LOWER LIMB MOTION AND MUSCLE ACTIVITY RESPONSES DURING HIGH VERTICAL STEPPING IN SUBMERGED AND NON-SUBMERGED CONDITIONS

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The purpose of this study was to investigate muscle activity of the trunk and lower extremities during high vertical stepping in submerged (aquatic) and non-submerged conditions. Twelve participants (mean age 27 years) performed a 40-cm vertical step in water-submerged and non-submerged conditions. Lower limb and trunk muscle activity was recorded using electromyography. A motion capture system was used to record angular displacement and forward trunk inclination angle. In submerged conditions, the hip joint demonstrated a larger range of motion, with the electromyogram revealing lower mean values and higher integrated values of muscle activity for selected musculature. It was considered that a low to moderate instantaneous stimulus, but high total stimulus was observed in the submerged condition. Aquatic rehabilitation training may be an effective tool in maintaining or regaining stepping ability.

KEYWORDS: muscle activity, stepping motion, activities of daily living, aquatic exercise, pool platform equipment.

INTRODUCTION: Aquatic exercise has been used to promote physical health and has been employed as a form of rehabilitative training. Typical activities of daily living (ADLs) such as walking, standing from a chair, and climbing steps, have been implemented in aquatic rehabilitation training programmes (Sato et al., 2007; Cuesta-Vargas, Cano-Herrera & Heywood, 2013). Prior research investigating ADLs performance in elderly populations have proven to be effective (Sato et al., 2007) with studies reporting electromyogram (EMG) and kinematic differences during submerged ambulation in young adults, elderly persons, and disabled persons (Barela & Duarte, 2008; Giaquinto et al., 2007; Kaneda et al., 2008). Previous research has reported non-treadmill submerged condition walking showing higher EMG activation in the lower extremity and trunk muscles than non-submerged conditions, although triceps surae muscle activation was decreased (Kaneda et al., 2008; 2009). These findings suggest that the properties of water, such as buoyancy and viscosity can affect EMG characteristics during exercise in submerged walking conditions. When young adults stand from a seated position, lower extremity and trunk muscle activation is significantly lower during submerged conditions compared with non-submerged conditions due to buoyancy (Cuesta-Vargas, Cano-Herrera & Heywood, 2013). Walking versus standing from a chair involves different vertical and horizontal components, where walking is primarily a horizontal motion while the motion of standing is predominantly vertical. Subsequently, muscle activity changes in the combined motion of step climbing may be of interest due to the dual directional components of stepping both upwards and forwards. No previous research has reported muscle activity, and lower limb and trunk kinematics, in a submerged state. This study aimed to investigate muscle activity and two dimensional kinematics associated with the high vertical step climbing motion in submerged versus non-submerged conditions.

METHODS: Twelve Japanese men (age: 27.8 ± 8.1 years; 175.7 ± 4.6 cm; 65.4 ± 7.2 kg) participated in this study. Participants were excluded if musculoskeletal pathology was present. Written informed consent was obtained from all participants in accordance with the Human Ethics Committee at the Chiba Institute of Technology. Participants performed a step up onto a 40-cm tall steel box at a self-selected comfortable pace.

Five steps were performed in each trial, with a total of three trials performed. A generic and 40 cm step height (Figure 1) was employed, similar to that utilised in a prior intervention study of Japanese frail elderly persons performing stepping exercise for rehabilitation (Sato et al., 2007). The participants conducted the step climbing trials in non-submerged and submerged conditions, in random order. A made-to-order water tank (Japan Aqua Tec Co., LTD, Japan) (Figure 2) with a one-sided glass window was used for the submerged condition, and a concrete floor adjacent to the water tank was used for the non-submerged condition. The water temperature was maintained at 31.0 ± 0.8 °C and the water depth filled to 1.0 m. A wireless EMG sensor (LP-WS1221, Logical Product Corp, Japan) (1 kHz) was placed on the right side of the tibialis anterior (TA), medial head of the gastrocnemius (GAS), rectus femoris (RF), long head of the biceps femoris (BF), rectus abdominis (RA), and erector spinae (ES) musculature. Attachment locations were consistent with the anatomical guide for EMG (Perotto et al., 1994). The EMG sensor was firmly water-proofed using transparent film and a specially fabricated seal (Foam Pad; Nihon Kohden Corp., Japan). An isometric maximal voluntary contraction (MVC) was performed for each muscle to express the all collected EMG data as a percentage of MVC values (%MVC). All EMG data, including the stepping exercise, were filtered using fourth-order high- and low-pass filters with 10-Hz and 500-Hz cut-off frequencies, respectively. The root mean square was then calculated with 100 ms windows of data. Step climbing joint and segment kinematics were captured using a motion capture system (VENUS 3D; Nobby Tech. Ltd, Japan) operating at 100 Hz. Cameras were positioned on the right side of the participants to capture sagittal plane two-dimensional (2D) motion. A wireless active marker (Kirameki; Nobby Tech. Ltd, Japan) was placed on the fifth metatarsal head, lateral malleolus, lateral epicondyle of the femur, greater trochanter, midpoint on the iliac spine, and acromion of the right side (Figure 2). Marker trajectories were low-pass filtered at 6 Hz with a fourth-ordered Butterworth digital filter. The 2D angular displacement of the ankle, knee and hip joint, and the trunk forward inclination angle from the absolute vertical axis (global) were calculated. Positive values denoted ankle plantar-flexion, knee and hip extension, and trunk forward inclination. Relevant EMG and motion data



Figure 1: Typical platform equipment used in Japan

were extracted throughout the entire phase of climbing motion based on ± 5 °/s of the right thigh's angular velocity (Figure 3) referencing a previous study (Kaneda et al., 2018), where the beginning was the moment when the upward motion of the right thigh started, and the end was when the downward motion of the right thigh stopped. Here, the negative value of the thigh segment angular velocity indicates upward direction and the positive value indicates downward direction. The subjects performed five steps in each trial, and the third step was extracted for analysis.



Figure 2: The made-to-order water tank and 40-cm steel box used as a step

Following data extraction, mean EMG (mEMG) and integrated EMG (IEMG) were computed as %MVC values. Joint and trunk inclination angles at the beginning and end of the extracted phase, and range of motion (ROM) across step climbing motion, were computed. The study averaged the second and third trials for each participant. A Kolmogorov-Smirnov test was applied to evaluate the normality of the data and an F test applied to examine the

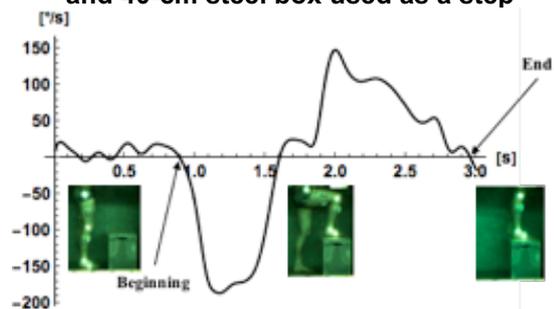


Figure 3: Beginning and end definitions based on right thigh angular velocity

equality between the two conditions. A Wilcoxon signed-rank test was used to detect differences between the two conditions for the non-parametric data, and a paired t-test was used for parametric outcomes. Statistical significance was set at $\alpha = 0.05$.

RESULTS: Non-submerged and submerged condition duration was 2.1 ± 0.3 s and 2.9 ± 0.3 s respectively, with a significantly longer duration in the submerged group. The mEMGs of the GAS, RF, and RA were significantly lower in the submerged condition (Table 1). However, there was a significantly higher mEMG observed in ES in the submerged condition. In the submerged condition, significantly lower IEMG was found in RF, and higher IEMGs were recorded in TA, BF, and ES (Table 2). The hip joint angle during early motion was significantly more flexed and extended at the motion endpoint in the submerged condition. Hip and knee joint angle ROM were also larger in the submerged condition.

Table 1: The mEMG of each muscle

	TA (%)	GAS (%)	RF (%)	BF (%)	RA (%)	ES (%)
Non-submerged	17.5 ± 5.6	10.7 ± 3.3	12.7 ± 7.4	7.4 ± 3.1	1.6 ± 0.7	16.7 ± 6.3
Submerged	19.8 ± 5.8	$8.1 \pm 3.2^*$	$7.7 \pm 2.3^*$	7.1 ± 3.8	$1.3 \pm 0.6^*$	$19.6 \pm 6.6^*$

*: $p < 0.05$; TA: tibialis anterior, GAS: medial head of the gastrocnemius, RF: rectus femoris, BF: long head of the biceps femoris, RA: rectus abdominis, ES: erector spinae

Table 2: The IEMG of each muscle

	TA (%)	GAS (%)	RF (%)
Non-submerged	36902.0 ± 12849.0	22870.6 ± 7961.7	26886.4 ± 11657.1
Submerged	$58164.9 \pm 14938.2^*$	22586.6 ± 8080.1	$21114.3 \pm 5634.5^*$

	BF (%)	RA (%)	ES (%)
Non-submerged	15280.5 ± 5124.0	3417.4 ± 1526.1	34204.8 ± 9924.5
Submerged	$20147.0 \pm 10454.0^*$	3674.8 ± 1411.6	$57568.6 \pm 20506.9^*$

*: $p < 0.05$; TA: tibialis anterior, GAS: medial head of the gastrocnemius, RF: rectus femoris, BF: long head of the biceps femoris, RA: rectus abdominis, ES: erector spinae

Table 3: Joint and trunk forward inclination angles

	Beginning			
	Ankle (°)	Knee (°)	Hip (°)	Trunk (°)
Non-submerged	109.4 ± 5.7	172.4 ± 5.3	163.6 ± 2.4	2.3 ± 4.5
Submerged	111.3 ± 6.8	171.1 ± 4.2	$145.7 \pm 8.1^*$	2.7 ± 3.8

	End			
	Ankle (°)	Knee (°)	Hip (°)	Trunk (°)
Non-submerged	109.8 ± 5.5	172.3 ± 5.5	161.8 ± 4.2	0.8 ± 6.3
Submerged	110.6 ± 7.5	167.6 ± 3.8	$170.1 \pm 3.4^*$	2.7 ± 4.4

	ROM			
	Ankle (°)	Knee (°)	Hip (°)	Trunk (°)
Non-submerged	26.1 ± 4.2	103.8 ± 4.8	48.9 ± 5.7	18.9 ± 6.0
Submerged	29.9 ± 5.4	$106.2 \pm 4.5^*$	$67.5 \pm 11.5^*$	20.8 ± 6.3

*: $p < 0.05$; ROM: range of motion; larger value indicates ankle planter-flexion, knee and hip extension, and trunk forward inclination.

DISCUSSION: This study investigated muscle activations and joint angle displacement in participants completing a 40-cm step height climbing motion in submerged versus non-submerged conditions. In the submerged condition, lower mEMGs in GAS, RF, and RA musculature was found, likely attributed to the influence of buoyancy. Weight load is reduced when immersed, which may have contributed to the lower mEMG in the GAS, a finding also reported in previous studies of walking and standing from a chair (Cuesta-Vargas, Cano-Herrera & Heywood, 2013; Kaneda et al., 2008). Larger RA mEMG was observed with chair standing in the submerged condition as the area of the submerged body parts continuously changed during motion, likely affecting balance (Cuesta-Vargas, Cano-Herrera & Heywood, 2013). RF is involved in hip flexion and knee extension with a reduced mEMG previously noted with chair standing (Cuesta-Vargas, Cano-Herrera & Heywood, 2013). The present study also found lower RF mEMG during submerged stepping suggesting a strong buoyancy influence during exercise. Only the mEMG of the ES was higher in the submerged condition than the non-submerged condition. A high mEMG of the ES was detected in the submerged walking and chair standing motions that was consistent with previous research (Cuesta-

Vargas, Cano-Herrera & Heywood, 2013; Kaneda et al., 2009). The ES activates when resisting the viscosity of water during walking, or balancing during chair standing. In addition, the larger hip joint ROM in the submerged condition also potentially affected the ES results, due to the anatomical relationship of hip joint motion affecting pelvis and trunk posture. The TA, BF, and ES showed high IEMGs in the submerged condition. In addition, only the IEMG of the RF was lower in the submerged condition than the non-submerged condition. The discrepancy between the mEMG results and the IEMG may be due to the difference in the duration of the stepping motion across the two conditions. IEMG is influenced by the length of time however mEMG is not. As such, mEMG expresses the instantaneous muscle stimulus, while IEMG expresses the total muscle stimulus. Compared with the non-submerged condition, the submerged step climbing exercise obtains a similar instantaneous muscle stimulus, but requires a larger total muscle stimulus of TA and BF; a lower instantaneous muscle stimulus, but a similar total muscle stimulus to GAS and RA; a lower instantaneous muscle stimulus and total muscle stimulus to RF; and finally, a larger instantaneous muscle stimulus and total muscle stimulus to ES. One of the merits of aquatic exercise is minimizing the impact of gravity stress (weight off-load) on the human body, allowing for motion that could not otherwise be performed under standard conditions (Batterham, Heywood & Keating, 2011). As such, aquatic exercise has been widely used to maintain health and to restore motion (Devereux, Robertson & Briffa, 2005; Marinho-Buzelli, Bonnyman & Verrier, 2015). The present study finds that an aquatic environment is effective in mitigating the instantaneous muscle stimulus during stepping exercise. However, it also indicates that the stepping exercise in the submerged condition burdens most of the muscles with greater total muscle stimulus (except the RF muscle).

CONCLUSION: The study investigated the impact of climbing a 40-cm tall step in submerged and non-submerged conditions on the muscle activity of young adults. The results showed a lower instantaneous muscle stimulus, but a higher total muscle stimulus in the submerged condition than in the non-submerged condition. These results indicate that the stepping motion in an aquatic environment may have been primarily influenced by buoyancy rather than viscosity during exercise. Aquatic rehabilitation presents an effective rehabilitation training tool to regain and prevent deterioration of a patient's stepping ability.

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