Title: **Standing on water: postural behavior while balancing on a stand-up paddle board**

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ABSTRACT

Humans can learn to maintain upright posture across a range of scenarios. For instance, when stepping from shore onto a stand-up paddle (SUP) board, humans adapt to a dynamic support surface that can move through both external factors (i.e., imposed forces from water) and self-generated actions (i.e., forces and torques delivered through the feet). Consequently, the brain must accommodate for the unique mechanical relationships between the body, board and water to stabilize upright whole-body posture. In the present study, we examined how humans balanced on a SUP board in water by analyzing whole-body kinematics of: (1) novices (to aquatic board sports) who trained to balance on the board, and (2) experienced participants who stood at different stance orientations and widths. When on the SUP board, novice and experienced participants exhibited body segment movements that were highly coupled to board motion as well as whole-body movement variability that increased compared to standing on land. During training, however, novice participants progressively reduced the movement variability of their upper body (head and torso) while allowing the board variability to increase. This was accompanied by a reduction in coupling (i.e., cross-correlation) between the body and board movements. When experienced participants stood with the body facing the board's width (i.e., surfer stance), whole-body movements were more variable as compared to when they faced the board's length (i.e., SUP stance). Surprisingly, however, wider stance widths were associated with greater movement variability. Our study demonstrates how human movement behavior is adapted for balancing atop a SUP board.

INTRODUCTION

The healthy human balance system can readily adapt to changing environments, ensuring stable and efficient postural control throughout daily life. During bipedal activities, the nervous system maintains upright posture by monitoring whole-body orientation and generating the appropriate motor actions needed to resist destabilizing forces (i.e., gravity, unexpected perturbations). When standing on solid, fixed surfaces, the brain maintains upright balance by generating muscle activity that ultimately results in reaction forces and torques through the interaction of the feet with the ground. The demands for the neural control of balance, however, become more complicated when standing on unstable surfaces. For instance, certain support surfaces, like those on trains or boats can translate and/or tilt due to external influences beyond our own control; however, they often provide a relatively stable platform against which we can produce balance-restoring forces. In contrast, unstable surfaces such as balance boards or sand, can move or change shape based on our own actions, such that maintaining standing balance requires the nervous system to calibrate its control to both the consequences of voluntary actions and the mechanical properties of the external environment.

Aquatic board sports, like stand-up paddling, are activities that involve maintaining standing balance on a dynamic support surface that can move through both external influences (i.e., imposed forces from water movement) and self-generated actions (i.e., forces and torques delivered through the feet). The increased popularity in stand-up paddle (SUP) boarding over the last two decades has led to research into its effects on physiology[1,2], injury epidemiology[3,4] and paddling motion kinematics[5]. However, little is known about how our nervous system adapts postural control to the unique mechanical relationships between the body, board and water in combination with the unpredictable balance perturbations imposed by water movement. In the present study, we examined the postural behavior of humans when they balanced on a SUP board on water. Our aims were to (1) establish how individuals adjust whole-body movements through training and (2) determine how the asymmetric dynamics of a SUP board influences postural behavior when standing at different stance orientations and stance widths.

When a novice first steps onto a SUP board, they must quickly familiarize to the novel task dynamics to minimize postural instability and the risk of falling. What changes in movement behavior can be expected as novices learn to balance on the board? Since the support surface (i.e., board) is susceptible to unpredictable perturbations (from dynamic water movement), the sensory cues provided by lower limb somatosensors are prone to greater variability (or noise) relative to standing on a fixed support surface. Consequently, the nervous system may compensate by dampening upper body movement to minimize noise from other sensory channels, such as the visual and vestibular sensory systems. Indeed, when standing on alternative unstable support surfaces, such as externally perturbed oscillating platforms or balance boards, humans have been observed to limit body segment motion in a descending organization with head movements preferentially minimized, followed by the torso, and lower body[6-9]. Therefore, we first hypothesized that through learning to stand on the SUP board, humans will minimize upper movement variability (i.e., head and torso) relative to lower body movements (i.e., pelvis).

We further questioned if and how the relationship between board and body motion (i.e., coupling) would change through learning the dynamic balance task. As participants balance for prolonged periods on the SUP board, they will gain experience with (1) the stability of the board and its effects on upright posture, and (2) the manner in which self-generated balance actions influence both the board and body motion. If the balance system equally prioritizes stabilizing the control of both the board and body, their kinematic coupling will be maintained or even increased during training. Alternatively, the balance system may prioritize the upright body over board stability, and consequently decrease board-body coupling with training. Irrespective of coupling between the board and body, we further expected that the coupling between body joint/segment angular movements would be enhanced when balancing on the SUP board relative to standing on land. This is because when standing on moving platforms, humans increase coupling (i.e., cross-correlation) between upper and lower body angular movements (i.e., stiffening of multi-segment linked bodies), potentially as a mechanism to generate the large forces and torques needed to stabilize the body[7,8,10,11].

Another important consideration for balancing on dynamic support surfaces is the influence of standing configuration (stance orientation and width) on whole-body behavior. Most often, paddlers adopt a “SUP stance” position to generate thrust in the water with a hand-held paddle, with the feet and body pointed along the board’s length (i.e., the long axis). Paddlers can switch to a “surfer stance” position, with the feet and body facing the board’s width (i.e., the short axis) when catching and riding a wave. Because of the board’s asymmetric dimensions, balancing motor actions will have differing consequences on body and board movement at these different standing orientations. For instance, balancing forces and torques applied to the board are expected to have a greater influence on the board’s roll as opposed to the board’s pitch. Given that anteroposterior whole-body motion is typically more variable than mediolateral motion when standing on land[12-14], we expected that standing in a surfer stance on the SUP board (body anteroposterior direction facing the board’s width) will result in a more variable postural behavior. Furthermore, changes in stance width are expected to influence board and whole-body movement behavior because increasing stance width (1) widens the base of the support, (2) increases coupling between hip and ankle joint movements, and (3) increases hip leverage allowing for greater torque generation delivered at the feet[12,15,16]. Consequently, we hypothesized that participants would reduce movement variability and increase mediolateral kinematic coupling when standing at wider stance widths on the SUP board.

MATERIALS AND METHODS

Participants

A total of 17 healthy adult participants (9 females, 8 males; age: 26.2 ± 6.4, weight: 71.7 ± 11.2 kg, height: 173.9 ± 9.7 cm; mean ± standard deviation) with no known history of neurological and/or balance deficits participated in these experiments. Participants in Experiment 2 (learning to balance on a stand-up paddle board) had no prior experience in aquatic board sports (e.g., stand-up paddling, surfing, kiteboarding). Participants in Experiment 3 all had prior experience with recreational stand-up paddling and/or surfing. For all experiments, the protocol was verbally explained before the experiment and written informed consent was obtained. The experiments were approved by the Human Ethics Committee at the University of Otago and conformed to the Declaration of Helsinki with exception of registration to a database.

Experimental set-up and design

Three experiments were conducted to study whole-body postural behavior while standing on solid ground and while standing on a stand-up paddle board floating on calm or rough water (see Figure 1). In Experiment 1, we characterized quiet standing behavior on solid ground (laboratory floor) at different stance widths. The aim of this experiment was to provide reference data of postural behavior of standing on land for comparison to behavior when standing on a SUP board in water. In Experiments 2 and 3, we examined postural behavior from the dynamic balance task of standing on a stand-up paddle board in a water environment. The aim of Experiment 2 was to determine how whole-body behavior changes as novices learn to balance on the SUP board. The aim of Experiment 3 was to determine how postural behavior is influenced by different standing orientations (stance angle relative to the board and stance width). In Experiments 2 and 3, participants stood on a stand-up paddle board placed in a swimming flume (SteamLiNZ, Invercargill, New Zealand). The flume is a 10-m long × 2.5-m wide channel through which the flow of water can be manipulated by three engines which drive turbines.

In all experiments, whole-body kinematics were measured using a Vicon three-dimensional motion tracking system (Oxford Metrics, Oxford, UK), composed of ten infrared cameras surrounding the participant. Reflective hemispherical markers (14 cm in diameter) were placed on different landmarks of the body to track 3D positional information. In Experiment 1 (standing on solid ground), adhesive markers were placed in accordance with the full-body plug-in-gait marker set (Oxford Metrics, Oxford, UK). Four markers were placed on the head (via Vicon head band with markers). Seven markers were placed on the torso at the C7 vertebral spinous process, T10 vertebral spinous process, sternal notch, xiphoid process of sternum, middle of the right scapula, and the acromion of each scapula. Five markers were also placed on each arm at the middle of upper arm, lateral epicondyle of the humerus, middle of the forearm, styloid process of the radius and ulna (wrist markers) and the dorsum of the hand. Four markers were placed on the pelvis, at both left and right anterior superior and posterior superior iliac spines. Four markers were placed on each leg at the thigh, lateral epicondyle of the femur (knee joint marker) and shank of tibia and lateral malleolus of the fibula (ankle joint marker). Finally, two markers were placed on each foot at the second metatarsal head and on the calcaneous (heel). Experiments 2 and 3 used the same marker set with additional tracking markers added to the lower body. Four markers were added to each leg at the thigh, medial epicondyle of the femur (knee joint), shank of the tibia and medial malleolus of the fibula (ankle joint). Two markers were also added for each foot at the level of the metatarsals on the medial and lateral sides. In addition to body markers, six markers were placed on the stand-up paddle board to track its position (see Figure 1 and Experimental procedure). In all experiments, the lab coordinate system (XYZ) was set using stationary markers in the testing environment. In Experiments 2 and 3, the width of the board was aligned with X-direction of the coordinate system and the length of board was aligned with Y-direction. Kinematic data was sampled at 200 Hz in all experiments.

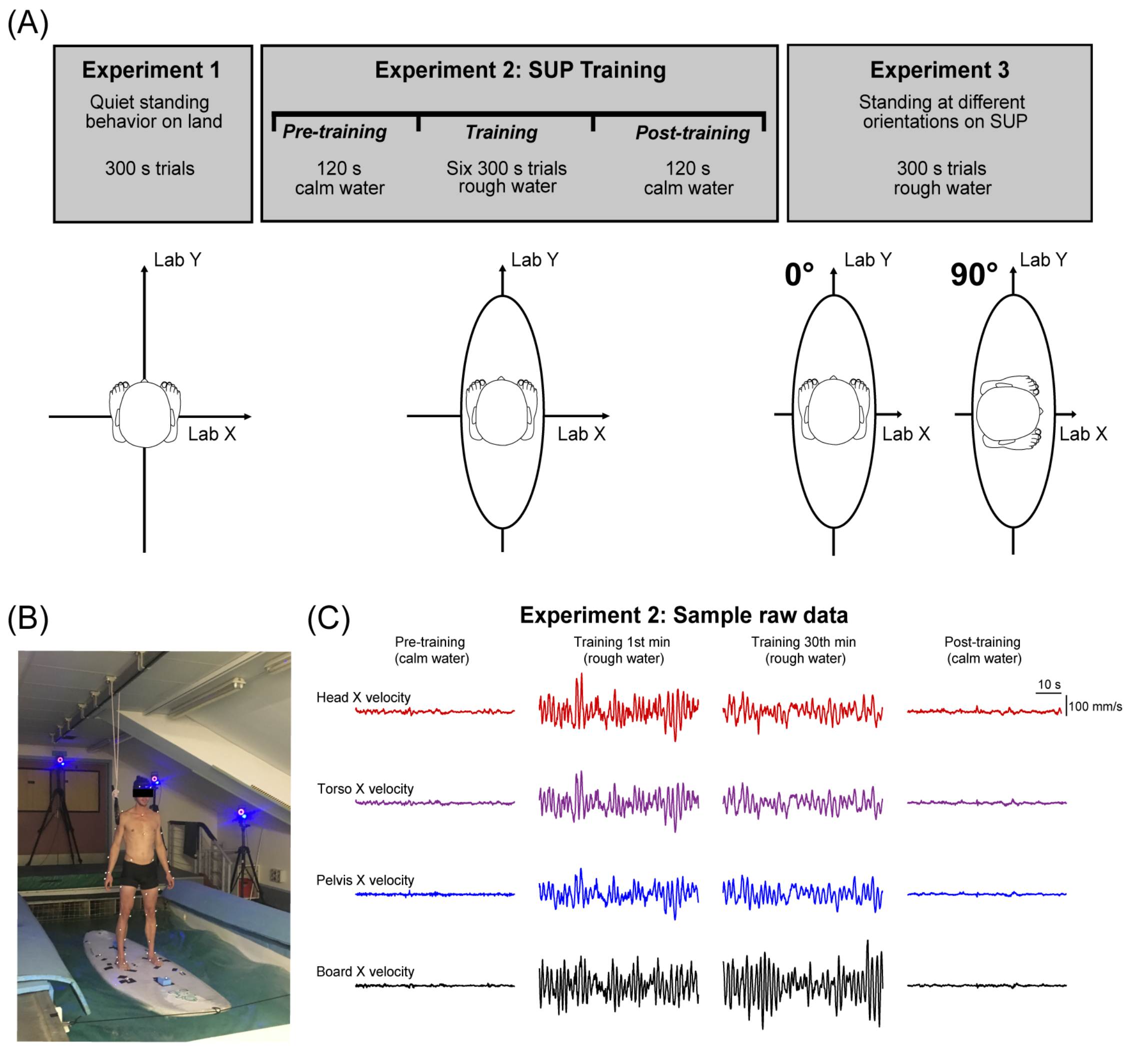

FIGURE 1. Experimental setup and example data. (A) Experiment 1 involved a group of participants (n = 8) standing quietly on land. Two of these volunteers participated in Experiment 2 and six participated in Experiment 3. Experiment 2 involved a group of novice (i.e., no previous experience in aquatic board sports) participants (n = 9) training for 30 minutes to stand

on a SUP board in calm and rough water flow conditions. Novice participants stood in a SUP stance in a 32 cm stance width for all trials. Experiment 3 involved a group of experienced (i.e., familiar with aquatic board sports) participants (*n* = 8) standing on the SUP board in different standing configurations during rough water flow conditions. Experienced participants balanced while standing at different stance orientations (0° SUP stance and 90° surfer stance) and widths (16, 32 and 48 cm). Illustrations depict the lab and body coordinate systems for each experiment. (B) Photo of participant standing on SUP board with reflective markers attached in the rough water condition. (C) Representative data of a participant in Experiment 2 balancing in the pre-training (calm water), training (rough water) and post-training (calm water) conditions. Data are raw traces of translational velocity of different body segments and the board in the X direction.

Experimental procedure

Standing on land

We first conducted a baseline experiment (Experiment 1) to characterize whole-body postural behavior while participants (*n* = 8) stood on a solid stationary surface. Participants performed two five-minute quiet standing trials with their eyes open. Trials were conducted with participants standing at two different stance widths: 16cm and 32cm (measured distance between the medial borders of the feet). Trials were randomly ordered across participants. Participants were instructed to look straight ahead with their hands by their sides and stand relaxed. Two of these volunteers participated in Experiment 2 and six participated in Experiment 3.

Stand-up paddle board experiments

In Experiments 2 and 3, we were interested in characterizing whole-body postural behavior while participants stood on a stand-up paddle board in the water. We tested SUP postural behavior in both a baseline condition with calm (i.e., laminar) water flow and a condition similar to open water environments (i.e., rivers and oceans), where the water flow is rough (i.e., turbulent) and causes unpredictable board movements. To create a calm water flow condition, all three flume engines were engaged which results in a laminar flow of water with relatively little turbulence once a constant speed is reached. To create a rough water flow condition, we disengaged the middle engine which left the two lateral engines operating to produce turbulent water flow. During all trials, the flume operated with a water flow speed set to ~2.0 m/s.

The SUP board was placed in the flume and tethered at its nose to the side walls of the flume using bungee cords. These restraints prevented the board from drifting to the back of the flume and allowed it to remain in a relatively consistent lateral position while water flowed through the flume. The board was 3 m in length and 0.85 m in width (measured at its widest point). Six reflective markers were placed on the board to track its motion during the experiments. The markers were placed to encircle the location the participants stood on. One marker was ~0.5 m anterior to the participant, one marker was ~0.5 m posterior to participant, two markers were ~0.3 m left of the participant and two markers ~0.3 m right of the participant. Tape markings were placed on the board to indicate stance positions for participants at the two standing orientations: 0° (feet oriented along the length of the board) and 90° (feet oriented along the width of the board). Markings were also placed at three stance widths (16 cm, 32 cm, 48 cm) for these two angles.

Depending on the experiment and condition (see below), participants were instructed to stand on the board at a defined stance orientation and width. They were asked to not shift their foot position during the trials but were permitted to move other parts of their body (i.e., tilt at the hips and torso, raise arms) to maintain balance. Safety foam was placed on the walls of the flume to protect the participant in case of a slip when getting on and off the board. A safety rope with a ring hand-holder was suspended from the ceiling. The rope was in reaching distance when the participants stood on the board, such that they could use it for external support between trials and during trials if they felt unstable. Participants were asked to only grab the safety rope during a recording trial if they felt extra support was needed to prevent them from falling, but this never occurred in any of the trials. To characterize how the SUP board moved in the flume in absence of any human control, we placed 70 kg of weights on the center of the board (where participants stood during balance trials) and recorded the motion of the board while the flume was running (for both calm water and turbulent water conditions). We present data from these board-only trials in Experiment 3 results.

In Experiment 2, novice participants ($n = 9$) stood on the SUP board in the flume in a traditional stand-up paddle posture (0°, body anteroposterior direction facing the length of the board) with a stance width of 32 cm. Trials were performed with the eyes open and participants were instructed to remain upright while standing on the SUP board. Participants first performed a pre-training trial, where they stood on the SUP board under calm water conditions (i.e., ~2.0 m/s with three flume engines engaged) for two minutes. Six five-minute training trials were then performed with participants balancing on the SUP board under rough water conditions (~2.0 m/s with two flume engines engaged), providing thirty total minutes of training. After every two training trials, participants stepped off the board and sat in a chair for a five-minute break. Once the six training trials were completed, participants performed a post-training trial that was identical to the pre-training trial (i.e., two minutes in calm water condition). After the experiment was completed, we conducted a short debrief session to obtain qualitative information regarding their experience balancing on the SUP board. First, we asked participants to describe their experience (i.e., how stable or unstable did you feel?) when performing the first trials on the stand-up paddle board, both in calm and rough water conditions. We then asked them to describe if they perceived changes in their behavior and confidence as they trained to balance in the rough water conditions.

In Experiment 3, six trials were conducted while experienced participants ($n = 8$) stood on the SUP board at two different stance orientations (0° and 90°) and three different stance widths (16, 32 and 48cm). Trials were randomly ordered across participants. At a standing orientation of 0°, the feet were parallel with the length of the board (i.e., traditional posture when paddling a stand-up paddle board as in Experiment 2), and at 90°, the feet were perpendicular with the length of the board (similar to a surfer stance). In board sports, people have different preferences with which foot goes to the front of the board and which goes behind when the body is facing perpendicular to the board's length. Some individuals prefer having the right foot behind and left foot in front (known as regular foot stance) while others prefer the reverse (known as goofy foot stance). Here, participants were permitted to adopt whichever stance was most comfortable but had to use this stance for all 90° trials. Five participants stood with a regular stance and the other three stood in a goofy stance. Each trial lasted five minutes with participants balancing on the SUP board under rough water conditions. Participants kept their eyes open and were asked to maintain a stable standing posture on the board. They were instructed to direct their head in the direction that their body was oriented but were permitted to intermittently turn their head if they wanted to view the nose of the board during the trial.

Data analysis

The 3D positions of the reflective markers were reconstructed offline using VICON processing software (VICON Nexus 2.9, Oxford Metrics, Oxford, UK). Missing data points (marker gaps) were interpolated using built-in Nexus functions. The 3D coordinates of markers were then exported for further analyses. Additional data analysis was performed using custom-designed routines on Matlab software (2022a version, Mathworks, Natick, MA, USA). To calculate body joint/segment angles, we used built-in Nexus functions.

Translational movement variability

Whole-body postural behavior in all experiments was characterized using exported marker trajectories. We first estimated translational motion (position and velocity) of the head, torso, pelvis and board. Marker position trajectories were low-pass filtered at 10 Hz. Head position was estimated by averaging the coordinates of the four head markers, torso position was estimated from averaging the coordinates from the C7 and sternal notch markers, pelvis position was estimated by averaging the coordinates from the four pelvis markers, and board position was estimated by averaging the coordinates from six board markers. Translational velocity was calculated by taking the time derivative of these head, torso, pelvis and board positions. We then calculated three kinematic variables using each of these time-varying segment translational velocity signals. The mean of the resultant XYZ velocities (i.e., speed) provided a metric of body movement magnitude independent of direction[12]. In addition, we calculated the variability of motion for each segment as the standard deviation of the translational velocity in the X- and Y-directions. For these measures, we refer to motion in the global (i.e., lab) coordinate system (X and Y), but we also describe movement in relation to the standing body direction (i.e., mediolateral or anteroposterior). Note that because the board can partially rotate relative to the global coordinate system, translational movements in the global coordinate system are not always purely mediolateral or anteroposterior with respect to the body.

In Experiment 1 (land) and Experiment 3 (SUP standing orientations), we calculated these mean speed and velocity SD measures over the entire trial (300 s). In pre- and post-training trials of Experiment 2 (SUP balance learning), we computed these measures over the entire 120 s trials. For the training trials of Experiment 2, we segmented the data into 1-minute intervals to provide a minute-by-minute tracking of postural behavior (i.e., mean speed and mean velocity SD) over the training period (total training time of 30 minutes).

Cross-correlation of board and body segments

We were interested in the level of coupling between the motion of the board and body, and how this coupling may be influenced by (1) training and (2) standing orientation. Therefore, we assessed the cross-correlation between the translational position of the board and different body segments (pelvis, torso and head). We used a Fourier-based analysis to estimate cross-correlations. For each trial of interest, data were cut into segments of 2048 data points (~10 seconds) providing a frequency resolution of ~0.098 Hz. For a given board-body segment pair (e.g., board-pelvis), the cross-spectra between segment positions were computed. Cross-correlations were then calculated by taking the inverse Fourier transform of the cross-spectra and normalizing it by the product of vector norms of the two signals (e.g., ankle and hip)[17]. This bounds the correlation estimate between -1 and 1, where -1 indicates a perfect negative correlation, 1 indicates a perfect positive correlation, and 0 indicates no correlation. To assess the level of coupling between board and body movements (independent of one segment leading the other in phase) we used the absolute value of cross-correlation estimates. Cross-correlations analyses were performed for board-pelvis, board-torso and board-head segment variables in both the X- and Y-directions. For Experiment 2, board-body segment cross-correlations were calculated using the entire trial length, including the pre- and post-training trials (120 s each) as well as the six training trials (300 s each). Similarly, Experiment 3 board-body segment cross-correlations were calculated using the full 300 s trials.

Joint and segment angle cross-correlations

Additionally, we were interested in how the coordination of body movements (i.e., coupling between joint and segment angular positions) differed from standing on land to balancing on the SUP board, and between different balance trials on the SUP. Therefore, in all experiments, we calculated angular kinematics throughout the upright body, including the ankle joints, knee joints, hip joints, torso segment and head segment angles using built-in routines in VICON software (Nexus 2.9, Oxford Metrics, Oxford, UK). All joint and segment definitions are described in Table 1. Using these angular position signals, cross-correlations were calculated between select pairs of signals (see below) in the pre- and post-training trials (120 s) as well as the first and final training trials (300 s). Angular position cross-correlations were computed using the same Fourier-based analysis as described for board-body segment cross-correlations.

Table 1: Definitions of estimated body joint and board angles

Body joint angle label	Definition
Ankle anteroposterior	Ankle dorsiflexion/plantarflexion
Ankle mediolateral	Ankle inversion/eversion
Knee anteroposterior	Knee flexion/extension
Knee mediolateral	Knee adduction/abduction
Hip anteroposterior	Hip flexion/extension
Hip mediolateral	Hip adduction/abduction

Segment angle label	Definition
X pelvis	Pelvis tilt in X-direction calculated about the laboratory transverse axis
Y pelvis	Pelvis tilt in Y-direction calculated about the laboratory transverse axis
X torso	Torso tilt in X-direction calculated about the laboratory transverse axis
Y torso	Torso tilt in Y-direction calculated about the laboratory transverse axis
X head	Head tilt in X-direction calculated about the laboratory transverse axis
Y head	Head tilt in Y-direction calculated about the laboratory transverse axis

Statistical analyses

The effects of stance width on body movements and joint motion couplings while standing quietly on land have been reported elsewhere[12,18-22]. Here, we were interested in using data from Experiment 1 (standing on land) to compare with data from Experiment 2 and 3 (standing on SUP board). Therefore, for selected variables, we performed pairwise comparisons (i.e., two-tailed t-tests) to assess whether postural behavior from standing on land differed to standing on the SUP board while controlling for stance width. When comparing land trials to calm water trials (i.e., pre- and post-training in Experiment 2), we used the first 120 seconds of land trial data so that it was of equal length as the calm water trials. On the other hand, because land trials and rough water trials (from Experiments 2 and 3) were both 300 seconds in length, we used the entire length of the trials for these comparisons.

Statistical tests were also performed to assess the effect of training in Experiment 2 and the effects of stance orientation and stance width in Experiment 3. For Experiment 2, we used two-tailed paired t-tests to compare how body segment motion (mean speed, mediolateral velocity SD, anteroposterior velocity SD) changed from pre- to post-training in calm water conditions. We further investigated how board and body motion changed in rough water training by using two-tailed paired t-tests to compare the first minute of training to the final (30^{th}) minute of training. To evaluate how board-body segment coupling changed from pre- to post-training, we compared cross-correlations using paired t-tests. We further used paired t-tests to compare board-body segment cross correlations from the first to the last training trial. If data was not normally distributed (tested using a Shapiro-Wilk test), pairwise comparisons were made using Wilcoxon signed-rank tests. In Experiment 3, we ran two-way repeated measures ANOVA's (independent variables: stance orientation × stance width) for mean speed, X velocity SD and Y velocity SD of each segment (i.e., board, pelvis, torso, head). We ran equivalent tests on board-body segment cross correlations (e.g., board-pelvis) and joint/segment angular cross correlations (e.g., ankle-hip). When using a two-way repeated measures ANOVA, a Greenhouse-Geisser correction was used for cases where sphericity was violated (Mauchly's test). Statistical tests were performed using

SPSS22 software (IBM) and the significance level was set at 0.05. Group data in text, tables and figures are presented as mean ± s.e.m. unless otherwise specified.

RESULTS

Experiment 1: Standing behavior on land

All participants who completed the quiet standing trials on land (Experiment 1) easily maintained a stable upright posture with limited postural sway (Figure 2A). Because this data serves as reference standing behavior for our SUP experiments, we present relevant results from Experiment 1 alongside the results of Experiments 2 and 3 in the sections below.

Experiment 2: Changes in postural behavior during balancing and training on SUP board

When participants inexperienced in aquatic board sports first stood on the SUP board in calm water conditions (Experiment 2), they typically described being cautious with their movements and concerned with the stability of the board, particularly in early trials. Indeed, their qualitative statements were accompanied by greater movement variability (i.e., mean speed, X and Y velocity) of all body segments (head, torso and pelvis) when standing on the SUP board relative to standing on land (Figure 2A, all $P > 0.05$). As expected, the variability of these kinematic measures increased further when participants began training in rough water conditions.

Over the training period in rough water conditions, all participants described feeling gradually more comfortable and confident at maintaining balance on the SUP board. This was accompanied by a progressive increase in movement variability of the SUP board. The mean speed of the board increased from 54.7 ± 2.7 mm/s in the first minute of training to 60.6 ± 2.5 mm/s by the final minute ($t_{(8)} = -1.87$, $P < 0.05$). This increase in speed was primarily due to increased movement variability in the X-direction, as board X velocity SD increased from 47.7 ± 3.7 mm/s in the first minute of training to 57.0 ± 3.1 mm/s by the final minute of training ($t_{(8)} = -1.99$, $P < 0.05$). No significant changes were observed in the board Y velocity SD (37.3 ± 1.7 mm/s vs 37.9 ± 1.8 mm/s; $P > 0.05$), which was not surprising since the board was relatively fixed in that direction via the tether. In contrast to the board, body segment movements decreased over training; mean speed decreased from the first minute to the last minute of training for the head (47.3 ± 2.4 mm/s vs 41.6 ± 2.1 mm/s, $t_{(8)} = 2.52$, $P < 0.05$) and torso (43.0 ± 2.4 mm/s vs 38.3 ± 1.4 mm/s, $t_{(8)} = 2.81$, $P < 0.05$). Similar to the board, these changes in speed were primarily due to change in movement variability in the X-direction (i.e., mediolaterally; see Figure 2 training, X-velocity SD) when comparing the first and final minute of training for both the head (37.4 ± 2.2 mm/s vs 31.6 ± 1.5 mm/s, $t_{(8)} = 2.47$, $P < 0.05$) and torso (33.6 ± 2.1 mm/s vs 29.0 ± 0.7 mm/s, $t_{(8)} = 2.40$, $P < 0.05$) segments. In contrast, pelvis X velocity variability marginally decreased by the end of training but this was not significant (32.5 ± 2.2 mm/s vs 31.9 ± 1.1 mm/s, $t_{(8)} = 0.49$, $P = 0.64$). Finally, for all body segments, there was no change in Y velocity variability when comparing the first and final minutes (all $P > 0.05$).

The changes in board and body movement variability observed over training were accompanied by a decrease in the coupling between the board and body segments. Specifically, there was a progressive decrease in cross-correlations between the board and all body segments in the X-direction (Figure 3). From the first to the final training trial, X-direction cross-correlations decreased for the board-pelvis by ~14% (0.86 ± 0.01 to 0.75 ± 0.02, $t_{(8)} = 5.38$, $P < 0.001$), for the board-torso by ~22% (0.76 ± 0.02 to 0.59 ± 0.02, $t_{(8)} = 6.90$, $P < 0.001$) and for the board-head by ~26% (0.72 ± 0.02 to 0.53 ± 0.03, $t_{(8)} = 5.92$, $P < 0.001$). Similar to movement variability of the board and body segments in the Y-direction, there were no changes in board-body cross-correlations in this direction over the training trials ($P > 0.05$). Overall, training in the rough water condition resulted in a decrease in both upper body movement variability and board-body coupling in the X-direction, though board movement variability increased. This suggests that participants reduced their body-on-board motion during the rough water training period.

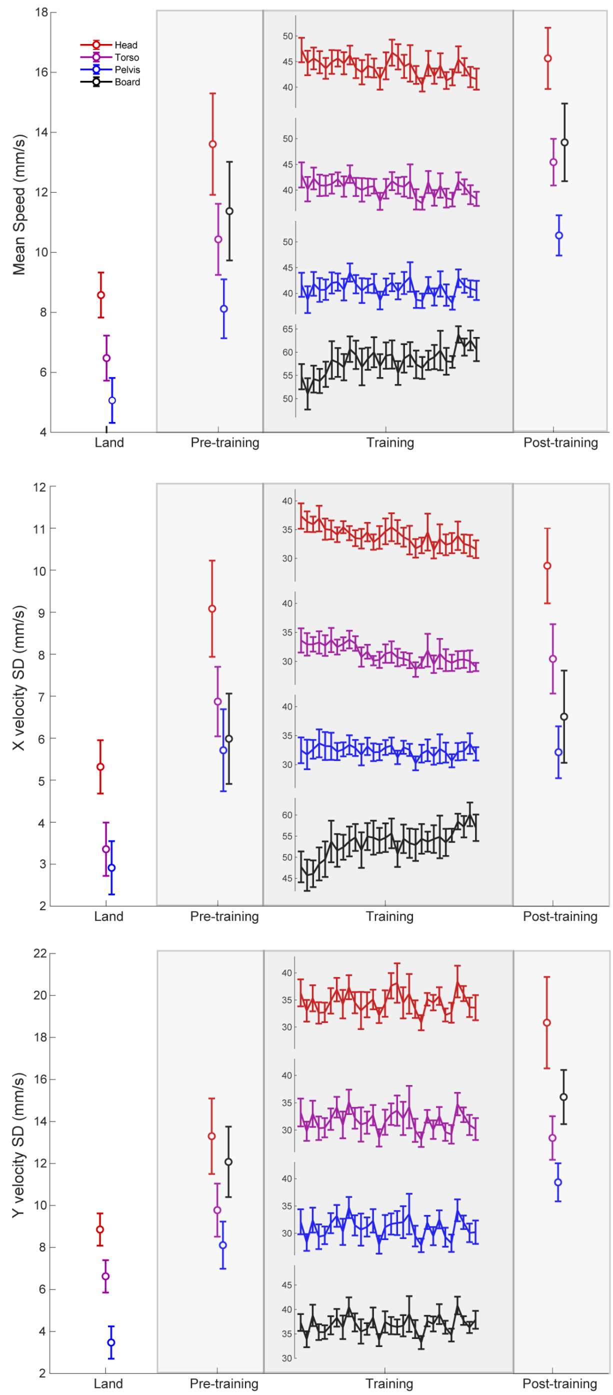

FIGURE 2. Translational motion variables (speed, velocity SD) of board and body segments on land (Experiment 1, *n* = 8) and SUP training (Experiment 2, *n* = 9). Land data is from the 32 cm standing trial (same stance width as Experiment 2 SUP trials). SUP data is from the pre-training (calm water), training (rough water) and post-training (calm water) conditions that were performed in a single session. Top panel presents mean speed, the middle panel presents X velocity standard deviations and the bottom panel presents Y velocity standard deviations. Training data is presented on a minute-by-minute basis over the 30-minute period of training. All

data is presented as means ± s.e.m. Shaded boxes are to indicate calm (pre- and post-training) and rough (training) water trials.

When returning to the calm water condition after the training period (i.e., post-training trials), body and board movement variability was greater as compared to the pre-training calm water trial (Figure 2). Mean speed increased from pre- to post-training for the torso (10.4 ± 1.2 mm/s vs 13.0 ± 0.8, $t_{(8)} = -2.41$, $P < 0.05$), pelvis (8.1 ± 1.0 mm/s vs 10.6 ± 0.7, $t_{(8)} = -2.43$, $P < 0.05$) and marginally increased for the head (13.6 ± 1.7 mm/s vs 16.5 ± 1.0, $t_{(8)} = -2.20$, $P = 0.051$) and board segments (11.4 ± 1.6 mm/s vs 13.7 ± 1.3, $t_{(8)} = -2.34$, $P = 0.051$). Although several segments showed slightly increased velocity SD in the X- and Y-directions from pre- to post-training (Figure 2), these were only significant for the board in the Y-direction ($t_{(8)} = -2.69$, $P < 0.05$). Similar to the increased movement variability, there were marginal increases in body-board segment coupling from pre- to post-training calm water trials in both the X- and Y-directions (Figure 3), but none of these changes were statistically significant (all $P > 0.05$).

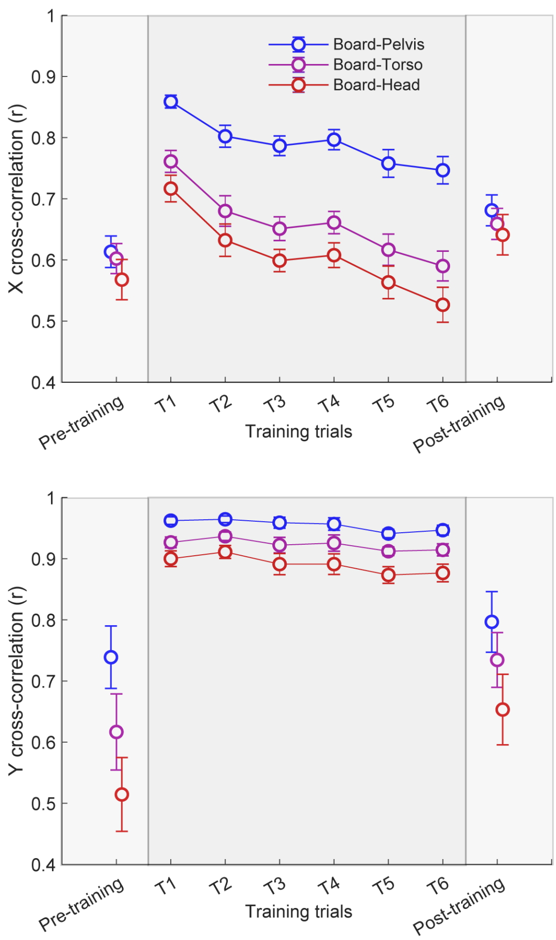

FIGURE 3. Cross-correlations between board and body (board-pelvis, board-torso, board-head) segment translational positions during SUP training (Experiment 2). Cross-correlations were computed from the full trial lengths (120 s for pre- and post-training, 300 s for training trials). Shaded boxes are to indicate calm water (pre- and post-training) and rough water (training) trials. All data are presented as means ± s.e.m.

Throughout these trials we also investigated how body joint/segment angular couplings varied (Figure 4). First, the estimated cross-correlation was larger on the SUP board than on land for several mediolateral (i.e., X-direction) angle pairs. Notably, mediolateral cross correlations were greater in the pre-training SUP trials compared to the land trial for the ankle-hip (~2× greater), ankle-torso (~2× greater), and ankle-head (~1.7× greater) (see Figure 3A and Table 3). This indicates that balancing on the SUP is associated with greater coupling between joint/segment angular movements in the direction of larger movement variability (i.e., width of the board). We further compared how angular coupling in calm water conditions changed after novices trained to balance on the SUP board. Only one difference in estimated inter-joint/segment cross-correlations was observed between pre- and post-training trials (ankle-torso AP motion) and between the first and final five-minute training trials (ankle-hip AP motion; see Figure 4 and Table 2). These results indicate that the learning that occurred in the rough water training protocol, which led to decreased body-board coupling, did not broadly influence coupling between body joint/segment angular movements.

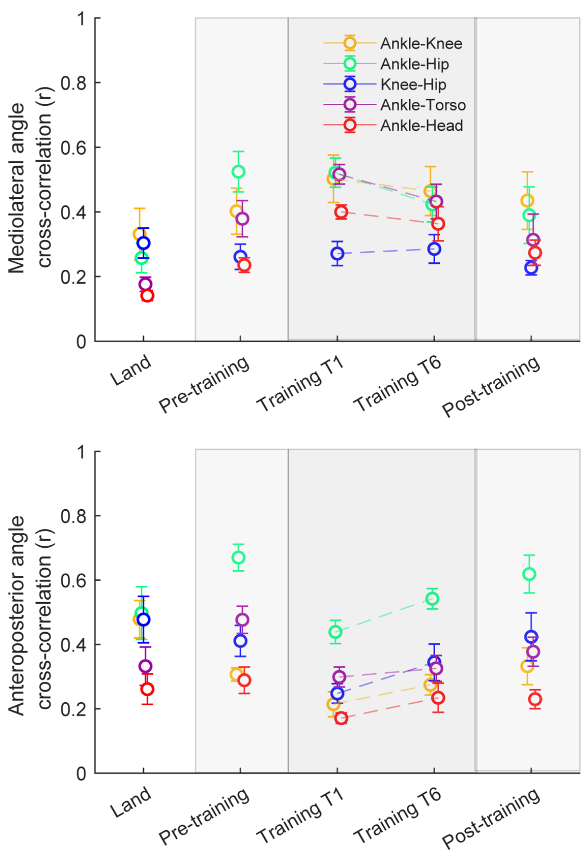

FIGURE 4. Cross-correlation values between angular measures in land trials (Experiment 1) and SUP balance trials (Experiment 2). Cross-correlations were estimated over the entire trial lengths. Mediolateral and anteroposterior coupling between body joint/segment angles from land, pre-training, first and last training and post-training trials are shown in the left column. Data is presented as means ± s.e.m.

Table 2: Summary of Experiment 2 body angular coupling statistical tests (p-values)

Variable	Ankle-Knee	Ankle-Hip	Knee-Hip	Ankle-Torso	Ankle-Head
land vs pre-training					
ML cross-correlation	0.515	0.004*	0.490	0.006*	0.005*
AP cross-correlation	0.010*	0.071	0.446	0.063	0.663
pre-training vs post-training					
ML cross-correlation	0.774	0.228	0.341	0.741	0.365
AP cross-correlation	0.800	0.363	0.743	0.037*	0.135
training-1 vs training-6					
ML cross-correlation	0.162	0.100	0.399	0.329	0.909
AP cross-correlation	0.236	0.022*	0.083	0.581	0.171

Pre and post-training trials were performed in calm water conditions. Training trials were performed in rough water conditions.

Experiment 3: Effects of standing orientation and width on postural behavior

All participants who had previous experience in aquatic board sports (i.e., Experiment 3) were able to maintain balance on the SUP board in the rough water condition while standing at different stance orientations and stance widths. Neither stance orientation nor stance width had any significant influence on the board's mean speed, X velocity variability or Y velocity variability (Figure 5B, all $P > 0.05$). We also measured board movement variability during passive trials (dotted lines in Figure 5B) where 70 kg of weights were placed on the board (no participant). When comparing the group average of participant standing balance trials to the passive weight trials, there were increases in mean speed (~19%) and X velocity variability (~56%) (Figure 5B, participant group data compared to dotted lines). This demonstrates that the board moved with greater variability in the rough water condition when participants actively balanced on the board.

In contrast to board motion, body movements were influenced by changing stance orientation and width (see Figures 5C, 6, 7B, and Table 3 for statistical summary). When standing at 90° (i.e., surfer stance), body segment movement (mean speed and velocity variability in both directions) was generally more variable compared to standing at 0° (i.e., main effect of stance orientation; Figure 5C). Mean speed increased when participants stood at 90° relative to 0° for the pelvis (34.3 ± 1.1 mm/s vs 40.2 ± 1.0 mm/s, $F_{(1,7)} = 18.46$, $P < 0.01$, $\eta_p^2 = 0.725$) and torso segments (35.9 ± 1.0 mm/s vs 39.1 ± 0.9 mm/s, $F_{(1,7)} = 6.44$, $P < 0.05$, $\eta_p^2 = 0.479$). These changes were primarily associated with increased variability in the Y-direction as the Y velocity SD also increased when standing at 90° relative to 0° for the pelvis (26.7 ± 0.8 mm/s vs 30.4 ± 0.7 mm/s, $F_{(1,7)} = 9.42$, $P < 0.05$, $\eta_p^2 = 0.574$) and torso (26.4 ± 0.6 mm/s vs 31.2 ± 1.0, $F_{(1,7)} = 17.69$; P < 0.01, $\eta_p^2 = 0.716$). Although X velocity SD slightly increased when standing at 90°, these changes were not significant ($P > 0.05$).

Changing stance orientation also influenced the coupling between board and body segment (pelvis, torso, torso) positions but only in the Y-direction (Figure 6 and Table 3); board-body coupling was larger in the 90° stance orientation relative to the 0° stance for the board-pelvis (0.98 ± 0.01 vs 0.88 ± 0.02, $F_{(1,7)} = 12.44$, $p < 0.05$, $\eta_p^2 = 0.640$), board-torso (0.97 ± 0.01 vs 0.83 ± 0.02, $F_{(1,7)} = 25.37$, $p < 0.01$, $\eta_p^2 = 0.784$) and board-head (0.94 ± 0.01 vs 0.75 ± 0.03, $F_{(1,7)} = 25.07$, $p < 0.01$, $\eta_p^2 = 0.782$) combinations. This indicates that there is greater board-body coupling in the direction of the board's long axis when the body's mediolateral direction is aligned with the board's length. Finally, there was a trend for greater coupling between inter-joint/segment angles (i.e., higher cross-correlation) in the direction of the body that was aligned with the board's width (Figure 7B). Consequently, mediolateral body joint/segment angle coupling was generally larger in the 0° stance angle, but this was only significant for the ankle-head coupling ($F_{(1,7)} = 8.34$, $p < 0.05$, $\eta_p^2 = 0.544$). Similarly, anteroposterior angular coupling was generally greater in the 90° stance orientation, and this was significant for the ankle-hip ($F_{(1,7)} = 9.50$, $p < 0.05$, $\eta_p^2 = 0.576$) and ankle-torso ($F_{(1,7)} = 34.62$, $p < 0.001$, $\eta_p^2 = 0.832$). Collectively, standing in the 90° (i.e., surfer stance) orientation was associated with increased body movement variability, board-body coupling, and inter-joint/segment angle coupling, as compared to the 0° SUP orientation.

Table 3: Summary of Experiment 3 statistical results (p-values). Statistical tests comparing the effects of stance orientation and width on movement variability and movement coupling.

Variable	Stance orientation		Stance width		Stance orientation × stance width interaction	
	F	p	F	p	F	p
Mean speed SD						
Pelvis	18.46	0.004*	4.44	0.032*	3.31	0.067
Torso	6.44	0.039*	2.53	0.326	1.21	0.326
Head	4.17	0.080	1.10	0.359	0.983	0.399
X velocity SD						
Pelvis	5.20	0.057	2.35	0.132	2.68	0.103
Torso	0.250	0.633	0.296	0.748	0.942	0.413
Head	1.72	0.231	0.01	0.990	0.757	0.488
Y velocity SD						
Pelvis	9.42	0.018*	4.42	0.032*	2.00	0.173
Torso	17.69	0.004*	7.05	0.008*	1.32	0.298
Head	0.07	0.0796	4.75	0.027*	0.33	0.728
X board-body cross correlations						
Board-Pelvis	0.896	0.375	1.52	0.252	0.340	0.718
Board-Torso	0.874	0.381	0.213	0.810	0.086	0.918
Board-Head	0.964	0.359	0.322	0.730	0.166	0.849
Y board-body cross correlations						
Board-Pelvis	12.44	0.010*	4.84	0.025*	4.10	0.080
Board-Torso	25.37	0.002*	8.20	0.004*	3.21	0.071

Board-Head	25.07	0.002*	4.68	0.003*	0.371	0.697
ML inter-joint/segment cross correlations						
Ankle-Knee	1.84	0.217	1.18	0.337	0.75	0.492
Ankle-Hip	3.78	0.093	1.38	0.284	1.83	0.197
Knee-Hip	0.070	0.799	0.55	0.591	0.92	0.422
Ankle-Torso	1.48	0.267	1.89	0.188	0.88	0.435
Ankle-Head	8.34	0.023*	1.10	0.362	0.33	0.725
AP inter-joint/segment cross correlations						
Ankle-Knee	0.47	0.517	0.83	0.455	0.42	0.664
Ankle-Hip	9.50	0.018*	1.78	0.206	0.07	0.931
Knee-Hip	0.13	0.725	0.06	0.947	2.60	0.110
Ankle-Torso	34.62	<0.001*	1.86	0.192	0.15	0.861
Ankle-Head	1.40	0.275	1.39	0.281	0.29	0.755

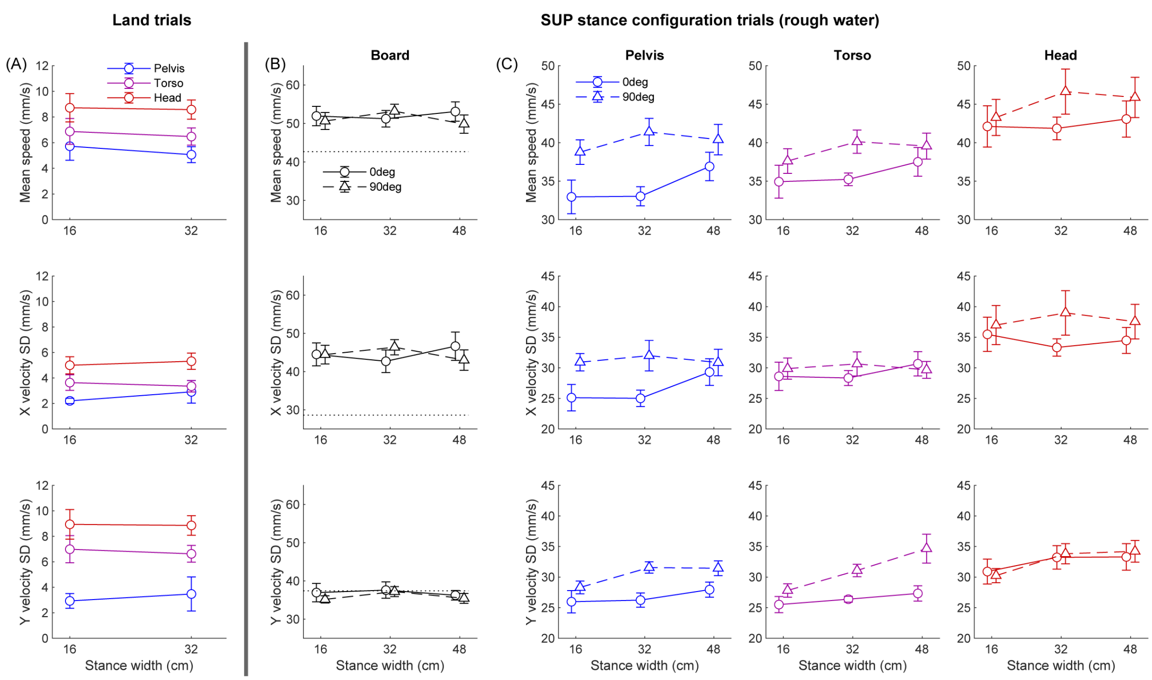

FIGURE 5. Translational motion behavior (speed and velocity variability) at different stance configurations on land (Experiment 1) and the SUP board (Experiment 3). (A) Effect of stance width on translational motion behavior for different body segments when standing on land (Experiment 1). (B) Effect of stance orientation and stance width on translational motion variables of board (X-direction is short axis, Y-direction is long axis of board) in Experiment 3. Circles and triangles represent 0° and 90° stance orientations, respectively. The dotted black lines represent translational motion variables for the board when 70kg of weights were placed on it (no participant). (C) Effect of stance orientation and stance width on translational motion variables of body segments in Experiment 3. Circles and triangles represent 0° and 90° stance orientations, respectively. All data are presented as means ± s.e.m. Grey vertical line is to

emphasize (A) data is from land trials, whereas (B) and (C) data are from rough water SUP trials.

In contrast to our expectation, increasing stance width on the SUP board was generally associated with increased body movement for both stance orientations (i.e., main effect of stance width; see Figure 5C). Mean speed increased with increasing stance width for the pelvis (16cm: 35.9 ± 1.5 mm/s vs 48cm: 38.7 ± 1.4 mm/s, $F_{(1,7)} = 4.44$; $p < 0.05$, $\eta_p^2 = 0.388$) and for the velocity SD in the Y-direction for the pelvis (16cm: 27.1 ± 1.1 mm/s vs 48cm: 29.7 ± 1.0 mm/s, $F_{(1,7)} = 4.42$, $P < 0.05$, $\eta_p^2 = 0.387$), torso (16cm: 26.7 ± 0.9 mm/s vs 48cm: 31.0 ± 1.6 mm/s, $F_{(1,7)} = 7.05$, $P < 0.01$, $\eta_p^2 = 0.502$) and head segments (16cm: 30.6 ± 1.1 mm/s vs 48cm: 33.8 ± 1.4 mm/s, $F_{(1,7)} = 4.75$, $P < 0.05$, $\eta_p^2 = 0.404$). Increasing stance width also resulted in increased board-body segment coupling (see Figure 6 and Table 3) in the Y-direction for the board-pelvis (16cm: 0.92 ± 0.02 vs 48cm: 0.95 ± 0.01 mm/s, $F_{(1,7)} = 4.84$, $P < 0.05$, $\eta_p^2 = 0.409$), board-torso (16cm: 0.88 ± 0.02 vs 48cm: 0.93 ± 0.02 mm/s, $F_{(1,7)} = 8.20$, $P < 0.01$, $\eta_p^2 = 0.539$) and board-head (16cm: 0.82 ± 0.04 vs 48cm: 0.87 ± 0.03 mm/s, $F_{(1,7)} = 4.68$, $P < 0.05$, $\eta_p^2 = 0.401$). Cross-correlations between inter-joint/segment angular movements, in contrast, were not influenced by stance width (see Figure 7 and Table 3). Finally, despite the significant main effects of stance orientation and width on several of the movement metrics, there were no significant interactions between these two variables on any measure. Taken together, standing movements on the SUP board are most variable when standing in a surfer stance at wider stance widths, and the coupling between the board and body is greatest when the body's mediolateral direction is aligned with the board's length (i.e., surfer stance).

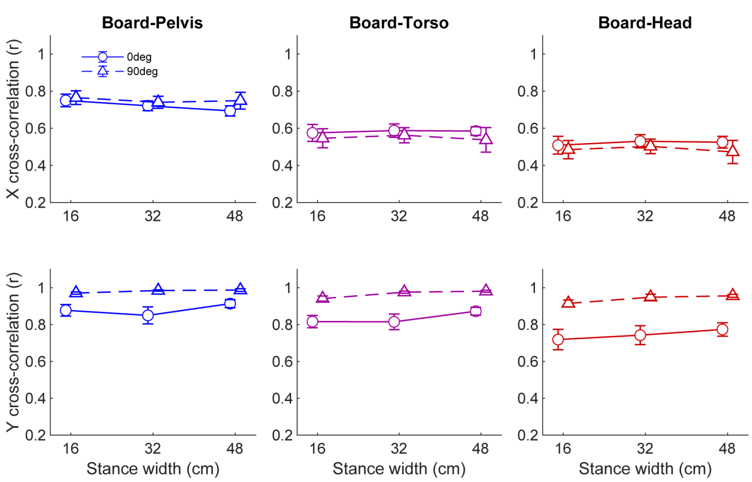

FIGURE 6. Cross-correlations between board and body (pelvis, torso or head) segments at different stance orientations and stance widths on the SUP board (Experiment 3). Top row presents data in the X-direction and bottom row presents data in the Y-direction. Circles and triangles represent 0° and 90° stance orientations, respectively. All data are presented as means ± s.e.m.

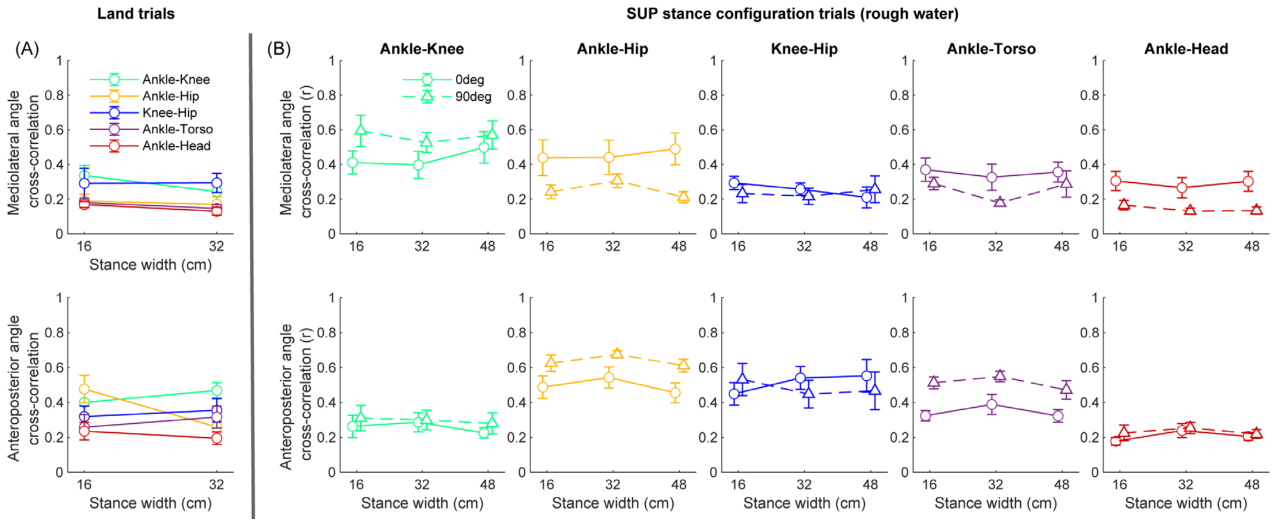

FIGURE 7. Cross-correlations between different joint and segment angles at different stance configurations on land (Experiment 1) and on the SUP board (Experiment 3). (A) Cross correlations between joint/segment angles when standing on land at different stance widths (Experiment 1). (B) Angle cross-correlations when standing on SUP board at different stance orientations and widths (Experiment 3). All data are presented as means ± s.e.m. Circles and triangles represent 0° and 90° stance orientations, respectively. Grey vertical line is to emphasize (A) data is from land trials, whereas (B) and (C) data are from rough water SUP trials.

DISCUSSION

These experiments investigated whole-body movement behavior when humans maintain standing balance on a SUP board floating on water. Due to the unique dynamics and task goals associated with balancing on the SUP board, we were interested in how postural behavior: (1) differs between standing on land and balancing on the board, (2) changes as novices learn this novel whole-body motor task, and (3) varies with stance orientation and stance width while on the board.

Comparison of postural behavior on land and water

When participants stood on the SUP board in both calm and rough water conditions, postural behavior was more variable compared to standing on land. Additionally, balancing on the board was associated with increased coupling between several body joint/segment angular movements in both the mediolateral (i.e., X) and anteroposterior (i.e., Y) directions. During unperturbed standing on a stable support surface, whole-body balance control arises through torques and rotations generated around the ankle and hip joints. When standing on dynamic support surfaces (i.e., balance board) and/or being exposed to external perturbations (i.e., oscillating platform), the center of mass is prone to larger and faster motion, forcing the nervous system to adjust the coordination of control over multiple body segments maintaining balance. Specifically, under these conditions balance control involves increased joint movements, greater coupling between joints and body segments, and the generation of larger motor actions (i.e., forces and torque) to control the center of mass position[23-25]. Indeed, when standing on the SUP board, we observed increased postural movements and greater coupling between body joint/segment angular movements. These results are consistent with previous findings of increased postural movement variability and joint/segment angular couplings when humans perform dynamic balance tasks that are more challenging than quiet standing on land[7,8,10,11,26]. Increased coupling between joints increases passive stiffness[12] and may be required to generate the forces and torques to keep the body upright when balancing on a dynamic support surface.

Learning to balance on a stand-up paddle board

Throughout training in the rough water condition, the variability of the board's translational movement in the X-direction progressively increased. In contrast, variability of the torso and head in the X-direction (i.e., mediolateral) progressively decreased in the X-direction (i.e., mediolateral; note, the pelvis exhibited little change). These inverse changes in board and body movement variability were accompanied by a gradual reduction in the coupling between the board and body segments (pelvis, torso, head) over the course of training. The reduction of upper body segment motion variability, particularly of the head, aligns with previously reported coordination of body movements as humans adapt control during dynamic balance tasks[7-9].

When initially standing on the SUP board, the mobility of the support surface ensures high variability (i.e., noise) in the somatosensory information derived from the lower limbs. To accommodate for increased variability of somatosensory cues during training, participants may adapt control by limiting noise from other balance-relevant sensory cues. For example, noise on visual and vestibular signals can be minimized by limiting the movement of the upper-body and head. This descending control hierarchy ensures that movements of the head and trunk are minimized throughout training to a greater extent than those of the hips and lower limbs[6,9,27]. Our results suggest that to stabilize the head and upper body, participants progressively decouple their body movements from board motion. When first standing on the board, participants are unfamiliar with (1) the stability of the board and its effects on upright stance, and (2) how self-generated balance actions influence both the board and body motion. Through practice, they experience how the rough water influences board motion, how the impact of their balancing motor actions on board and body movement, and what acceptable range of movements and forces will allow them to maintain an upright posture during the task. After prolonged experience in these conditions, participants appear to establish a strategy in which they minimize head and upper body movements by partially decoupling body movement from the board.

Despite the changes in movement variability and board-body coupling that occurred through training, coupling between body joint/segment angular movements did not change between the start and end of training (rough water trials), or between pre-training and post-training (calm water trials). This was contrary to our hypothesis and contrasts with other findings of inter- joint/segment coupling reducing as participants learn novel motor tasks[11,26,28-30]. Our results may be a consequence of the coordination requirements when balancing on the SUP board (either before, during or after training), where increased coupling in body joint/segment angular movements are needed to adequately control the larger center of mass movements while standing on the SUP board, as compared to standing on land.

Stance configuration on SUP board influences whole-body movements

We further found that changing stance configuration while balancing in the rough water condition on the SUP board influenced whole-body movement behavior. Standing in a surfer (90°) stance was associated with greater body movement variability and enhanced board-body coupling relative to a SUP (0°) stance, specifically in the direction of the body aligned with the board's length (i.e., Y-direction). Changes in standing orientation also influenced the coordination of body joint/segment angular movements, as coupling between different joint/segment angular positions (specifically ankle-hip and ankle-torso) increased in the direction of the body that was aligned with the width of the board (i.e., X-direction). Increasing stance width, on the other hand, resulted in greater body movement variability and board-body coupling, particularly in the direction of the board's length (Y-direction). There were no clear interactions of stance orientation and stance width on any of the dependent variables.

Due to the board's long length and shorter width, both the board and body are more susceptible to translations and rotations in the direction aligned with the board's width. When standing in a SUP (0°) position (body facing long axis), the balance system's control over board motion in its width (X-direction) is primarily achieved by modulating the load between the two legs through lateral torso tilt, hip adduction/abduction and adjusting inversion/eversion torques at the ankles. In contrast, when standing in a surfer stance (90°) position (body facing along board's width), controlling the board motion in the short direction is achieved by balancing actions in the body anteroposterior direction (i.e., hip flexion/extension and ankle dorsiflexion/plantarflexion). Our findings that body movement variability is greater in the surfer stance suggest that balancing on the board in this postural configuration is more challenging for the balance system. Although this instability may be primarily associated with controlling the board's short direction with muscles acting in the body's anteroposterior direction, the effects can cross over to the body's mediolateral direction due biomechanical interactions. For instance, because various muscles can generate balancing torques in both the anteroposterior and mediolateral body directions[31-34], instabilities in one direction can be reflected in the other.

Contrary to our expectation, increasing stance width on the SUP board resulted in greater variability in body movements. This may have been a consequence of the neuromechanical changes associated with wider stance widths and their interaction with the balancing on the board. At wider stance widths, hip leverage increases such that a given hip-generated torque will result in greater torques delivered through the feet to the support surface[15,35]. Consequently, at wide stance widths hip muscle actions should result in greater body center of mass movement, which can also occur over a greater range since the mediolateral base of support is widened. When balancing in the rough water condition, the nervous system must consistently respond to support surfaces perturbations (i.e., board motion from water movement). The enhanced mechanical gain that are inevitable at wider stances may therefore result in greater body motion through perturbation-evoked balance responses. This may result in greater motion in both the mediolateral and anteroposterior directions of the body, given the aforementioned biomechanical interactions between directions of standing balance[31-33,36].

Limitations

A limitation of this work is that the SUP board was tethered at the front (to prevent the board from hitting the sides and ends of the flume pool), which partially constrained its motion in the direction of the long axis. Therefore, our experiment is not an exact representation of open water SUP environments where the board is unattached to any external support. Nevertheless, our study provides insight into how postural behavior (i.e., movement variability, body-board coupling and inter-joint/segment coupling) changes between standing on land and balancing on a SUP board in different water conditions.

Future directions

Aquatic board sports – like stand-up paddling and surfing – have experienced a boom in popularity over the last two decades[3,4], with research studies focusing on their fitness and health benefits[1,2,5,37-39]. Our findings characterize whole-body kinematic behaviors of balancing on an SUP board (contrasting them with movements on land) and demonstrate how learning this unique task involves a reduction of upper body movement variability and reduction of the coupling between board and body movements. We further demonstrate how changes in standing configuration on the SUP board affects postural behavior and discuss the complex interactions between biomechanics, board stability, and the neural control of balance. Future research should consider how different sensory cues are relied upon to maintain and adapt upright balance during aquatic board sports. Notably, the trend to stabilize the head when balancing on the SUP board may suggest that the brain increases its dependence on vestibular and visual signals to control balance atop the board. Applying vestibular (e.g., electrical vestibular stimulation) and/or visual (e.g., moving visual scene) perturbations while participants balance on the SUP board may provide insight into how the sensory contributions to balance are modified when standing in these unique environments.

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