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KINEMATICS OF STATIONARY SPRINT KAYAK BALANCE CONTROL

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Abstract

This study investigates the kinematic characteristics of balance control in stationary sprint kayaking. Researchers analysed the motion of body segments and the kayak under three distinct conditions: voluntary rolling, static balance with minimal movement, and static balance with controlled oscillations. The results indicate that experienced kayakers demonstrate better control and symmetry in their kayak motion compared to less experienced individuals. The pelvis plays a primary role in initiating kayak motion, while the trunk remains relatively stable. The head and shoulders contribute to balance by counteracting excessive oscillations, particularly during the voluntary rolling task. The study concludes that balance control in sprint kayaking is a complex skill involving the coordinated movements of various body segments and suggests that targeted training can enhance an individual's balance abilities. This research provides valuable insights that could inform the development of kayak balance training aids capable of simulating the medial-lateral rolling motion experienced on the water. This study also outlines the potential for developing technology-based balance training tools to train new athletes and improve the performance of experienced athletes.

Keywords: sprint kayak, kinematic, balance control

INTRODUCTION

Balancing a stationary sprint kayak is an extremely demanding task for novice paddlers but relatively straightforward for experienced athletes. Sprint racing kayaks are slender, hollow shells, tapered at both ends, and propelled over water by human power using paddles (Michael et al., 2009). Maintaining balance and postural stability is a critical factor in many sports, as it allows athletes to optimize their movements and achieve peak performance. In the context of sprint kayaking, balance control is particularly crucial, as the paddler must remain stable on a narrow, unstable base to efficiently generate propulsive forces (Jaffri et al., 2019). Moreover, the paddler's centre of mass is situated above the kayak's centre of rotation, presenting a unique balance challenge. This elevated position of the paddler's mass centre relative to the kayak's pivot point requires the athlete to exert precise control over their body movements to maintain stability on the narrow, unstable platform (Michael et al., 2009).

Research examining the impact of balance training on 200-meter kayaking athletes has demonstrated a positive correlation between balance and performance (Hermawan et al., 2021). Specifically, the study indicates that 71.2% of the total variation in 200-meter kayakers' performance can be attributed to balance. This suggests that enhancing balance skills can significantly improve a kayaker's performance outcomes. However, it is important to recognize that balance is not the sole determinant of success in sprint kayaking. The same study acknowledges that the remaining 28.8% of performance variation is influenced by various other factors, such as weather conditions, mental state, boat condition, nutrition, recovery, and the athlete's overall health (Hermawan et al., 2021). Therefore, while balance is a critical element, it is part of a more complex interplay of elements that contribute to successful sprint kayaking performance.

The existing literature has investigated diverse methods for evaluating and developing balance skills across various athletic populations, but the unique demands of maintaining balance on a stationary sprint kayak have not been extensively examined (Brachman et al., 2017). While the purported objectives and benefits of balance training for athletes, such as performance enhancement and injury prevention, seem straightforward, the most effective training protocols remain unclear (Brachman et al., 2017). Additionally, the specific neuromuscular and sensory mechanisms that underlie balance control in the context of sprint kayaking have not been fully elucidated. Kinematic analysis of the interactions between body segments has provided researchers with enhanced knowledge and understanding of human balance control in a seated position. Studies have found that pelvic and hip kinematics play a prominent role in eliciting postural responses when sitting on an unstable platform (Blenkinsop et al., 2017; Qu et al., 2007; Marinkovic et al., 2021; Molnár & Insperger, 2022). This suggests that individuals may employ pelvic and hip strategies to maintain balance in an unstable seated position. Furthermore, multi-segmental kinematic analysis has offered improved insight into the complex, task-dependent motion of the human body during unstable sitting scenarios.

Building on these findings, this study aims to address the gap in the literature by quantifying kinematic data on the frontal plane motion of a kayak during three distinct on-water balancing tasks. It also seeks to investigate the strategies employed by paddlers to maintain balance on a stationary sprint kayak under varying conditions. By providing novel information on the role of body segment coordination in balance control, this research could inform the development of targeted training aids capable of simulating the medial-lateral rolling motion experienced on the water. Such advancements have the potential to enhance training protocols and performance outcomes for sprint kayaking athletes. The study hypothesized that experience in kayaking affects balance control ability, with more experienced kayakers demonstrating more symmetrical and stable control when performing static and dynamic balance tasks. Specifically, pelvic movements had a strong positive correlation with kayak orientation during dynamic balance tasks and experienced kayakers showed lower magnitudes of movement in the head and shoulder segments than less experienced kayakers during static balance tasks.

METHODOLOGY

Eight male kayakers, with competitive experience ranging from the national to university level, volunteered to participate in this study. This sample size was deemed sufficient as the participants represented a range of skill levels, enabling the study to capture variations in balance control strategies while maintaining focus on the elite and semi-elite athletic population. Furthermore, the use of a homogeneous group minimized confounding factors, such as differences in age, gender, or training background, which could otherwise impact the generalizability of the results. The participants had a mean age of 18 ± 2 years, mean height of 180 ± 8 cm, mean mass of 77 ± 7 kg, mean sitting height of 94 ± 4 cm, and a mean paddling experience of 9 ± 4 years. Before any data was collected, the testing procedures were explained to each subject in accordance with ethical guidelines; an informed consent form and a health screen questionnaire were signed. Eight retro-reflective markers were placed on the subjects to define the pelvis, trunk, shoulder and head segments. In addition, two markers were attached to the left and right sides of the kayaks deck. The midpoint of the two markers on the kayak was used to correct for lateral drift. The participants were given adequate time to familiarize themselves with the kayak and testing environment. They were then instructed to perform three frontal plane stationary balancing tasks: Task A - maintaining balance while voluntarily rolling the stationary kayak with a controlled motion while holding the paddle at shoulder height; Task B - maintaining stationary balance while holding the paddle at shoulder height; Task C - maintaining stationary balance with their arms folded across their chest. The marker placement and experimental task conditions are depicted in Figure 1.

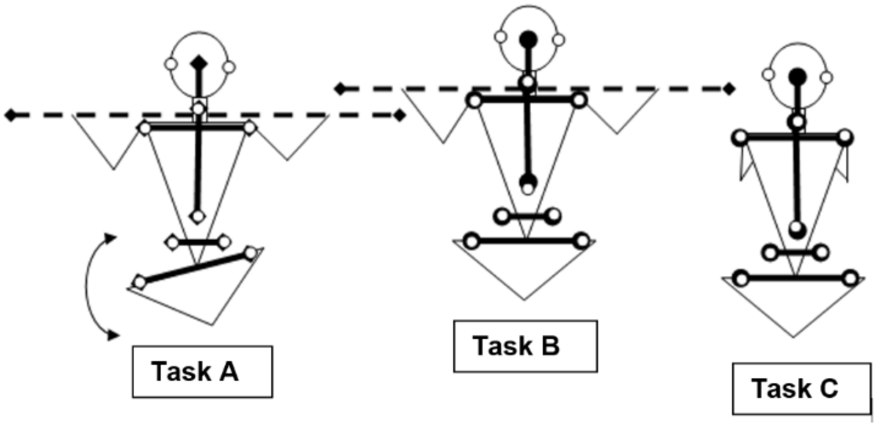


Figure 1: Experimental task conditions and the placement of retro-reflective markers

The study took place in a standard 50-meter swimming pool. A 50 Hz digital camera with a 1/300 s shutter speed was used to record video of each trial. To capture frontal plane medial-lateral motion, the camera was positioned behind the subject and angled perpendicular to the plane of balancing motion. The performance area was delineated by two white marker buoys placed laterally two meters apart. A custom-built start block device was anchored in the middle of the performance area, approximately 2 meters in front of the white marker buoys. This device served as a guide to ensure the kayak and paddler were positioned within the required field of view. The AviDigitiser software was utilized for the digitization process. This software employs a 'sub-pixel' cursor, allowing the centre points of the markers to be digitized with a precision of up to 0.1 pixels, potentially enhancing the accuracy by a factor of ten. Additionally, the software employs interpolation techniques to generate smoother, zoomed-in images, thereby improving the visibility of the desired points. To maintain consistency in the digitization procedure, a single operator was responsible for digitizing all the video recordings. Furthermore, to assess the digitization precision, the researcher repeated the digitization of some trials, and the resulting root mean square difference was found to be less than 2 mm.

To describe the participants' balance strategies in the frontal plane, several kinematic measures of translation and rotation were utilized. The horizontal and vertical linear displacements of the segment centres were identified as the sway and heave translational motion characteristics of the kayak-paddler system. The standard deviation of the medial-lateral displacement was employed as a measure of segment stability during the balancing tasks. The angular orientation of the kayak, pelvis, and shoulder was determined by calculating the angle between the medial-lateral axis and the line connecting the two markers representing those segments. Conversely, the head and trunk angular orientation were calculated using the angle between the vertical (Y) axis and the line connecting the respective marker pairs. Alignment of the segments near zero degrees indicated equilibrium, with positive angles for $y>0$, $z>0$ and negative angles for $y<0$, $z<0$. Pearson correlation was utilized to statistically examine the relationship between kayak motion and the orientation of body segments in maintaining balance and equilibrium across the performed tasks.

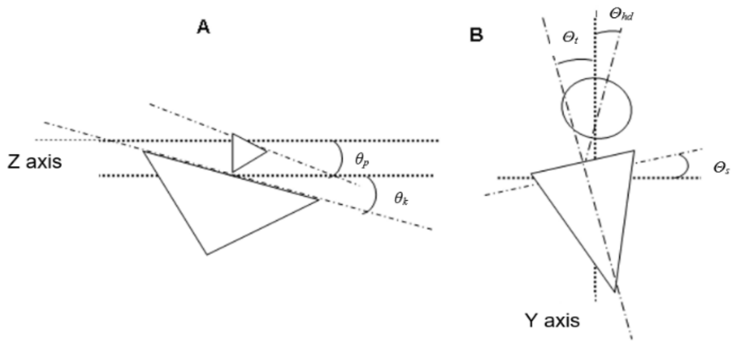


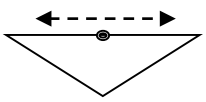
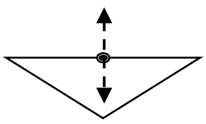
Figure 2: Angular orientation determination: **A.** kayak (θ_k) and pelvis (θ_p); and **B**. head (θ_{hd}), shoulder (θ_s) and trunk (θ_t)

RESULTS

Kayak linear and angular motion characteristics

Table 1 shows the mean kayak medial-lateral displacement (sway) was largest in Task A (45 ± 8 mm) compared to Task B (24 ± 12 mm) and Task C (17 ± 7 mm). This was due to the voluntary lateral rolling of the kayak by the subject. The highest sway range was 57 mm for subject S6, while the lowest range was 35 mm for subject S5. Kayak vertical displacement (heave) motion in this test (mean stability magnitude 4 ± 1 mm) was significantly smaller compared to the medial-lateral (sway) motion (mean stability magnitude 13 ± 2 mm). The highest vertical displacement range was 25 mm for subject S7, and the lowest was 12 mm for subject S5. As expected, the heave movement was minimal and mainly caused by the difference between the kayak's centre (calculated at the midpoint of two markers on the kayak deck) and the whole kayak-paddler system's centre of rotation.

Table 1: Medial-lateral (sway) and vertical (heave) displacement range and magnitude (SD) of the kayak centre

			Range	SD
	Sway	Task A	45.0 ± 8.0 mm	13.0 ± 2.0 mm
		Task B	24.0 ± 12.0 mm	6.0 ± 4.0 mm
		Task C	17.0 ± 7.0 mm	4.0 ± 2.0 mm
	Heave	Task A	20.0 ± 6.0 mm	5.0 ± 1.0 mm
		Task B	11.0 ± 2.0 mm	3.0 ± 1.0 mm
		Task C	15.0 ± 6.0 mm	4.0 ± 2.0 mm

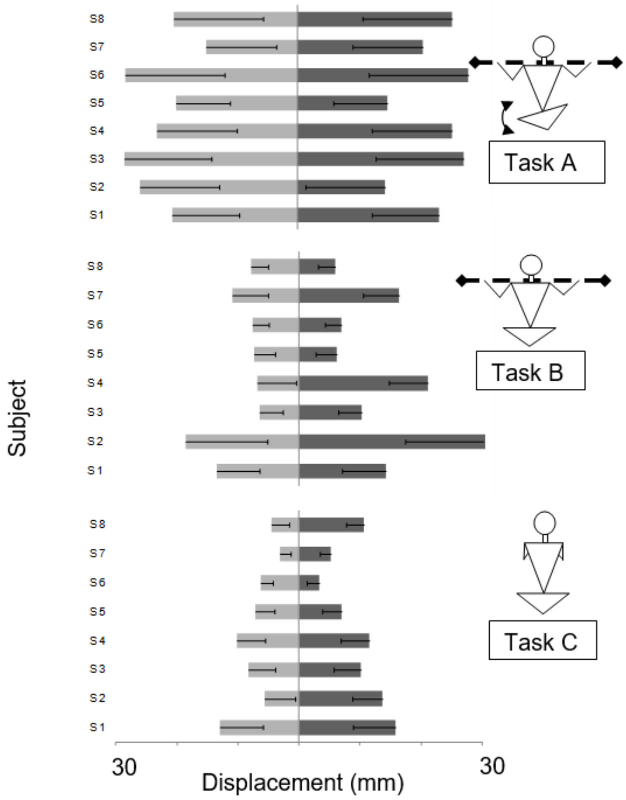


Figure 3: Kayak medial-lateral displacement (sway) range for all subjects in three task conditions

Table 2 shows the mean right and left roll angle produced by subjects in three test conditions. With voluntary initiation of kayak rolling motion, medial-lateral roll angle for anticlockwise rotation was 25° ± 5° and -24° ± 4° for clockwise rotation. The highest medial-lateral roll angle range produces were 65° by subject S8 (Figure 4). Meanwhile, subject S1 produce the lowest medial-lateral roll angle range of 41°. As illustrated in Figure 4, subject S3 and S6 was able to maintain a symmetrical angle between right and left dynamic rolling motion (Task A), with 28° anticlockwise and -25° clockwise respectively. On the other hand, the rest of the subjects showed more variability between anticlockwise and clockwise roll angle, with differences ranging from 2° to 6°. The static nature of balance control in Task B and Task C produced much lower roll motion compared to the dynamic condition in Task A. Between both conditions Task B produced lesser roll motion than Task C, with mean magnitudes of 3° ± 3° and 4°± 3° mm respectively. However, high standard deviation or magnitude indicated that most subjects were unable to maintain left and right symmetry (Table 2 and Figure 4).

Table 2: Kayak roll angle and magnitude (SD)

	Anticlockwise angle	Clockwise angle	SD
Task A	25.0° ± 5.0°	-24.0° ± 4.0°	15.0° ± 3.0°
Task B	7.0° ± 8.0°	-6.0° ± 7.0°	3.0° ± 3.0°
Task C	8.0° ± 7.0°	-7.0°± 8.0°	4.0°± 3.0°

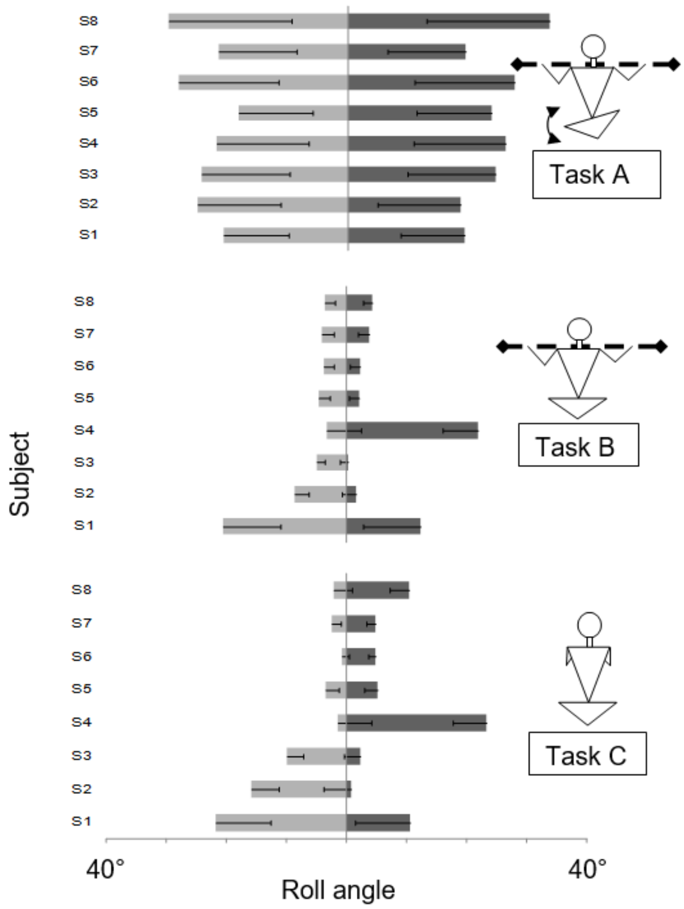


Figure 4: Kayak medial-lateral roll angle range for all subjects in three experimental conditions

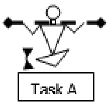
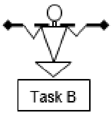
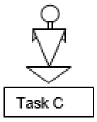
Relationship between segments and kayak orientation

The findings suggest that medial-lateral body motion in the frontal plane during stationary balance control is best described by a multi-segment model, with several body parts contributing to the regulation of balance. To investigate the control strategies employed by paddlers during three stationary balance tasks, the researchers examined the orientation of the pelvis, trunk, shoulders, and head relative to the kayak orientation (Table 3). As anticipated, the kayak's rolling motion was primarily governed by the continuous loading and unloading movements of the pelvis. The high positive correlation coefficient (Pearson $r > 0.50$) indicated that the pelvic motion was proportional to the direction of the kayak's movement across all task conditions. This relationship was most pronounced during the voluntary initiation of lateral kayak rolling in Task A ($r = 0.9$). These findings suggest that the medial-lateral rolling motion of the pelvis segment was the dominant response in regulating the angular orientation of a stationary racing kayak (Figure 5 and Figure 6).

Across all three task conditions, the trunk segment exhibited the smallest angular displacement compared to the other body segments. Furthermore, in Task A where the kayak underwent highly dynamic voluntary movement, the trunk segment oriented itself with a relatively small magnitude in the opposite direction of the kayak's motion, as indicated by the high negative correlation ($r = -.73$, shown in Table 3). The trunk angle range was minimal in comparison to the kayak angle range across all task conditions. The roll angle data presented in Figure 5 and Figure 6 suggested that the subjects employed a trunk stiffness strategy to limit excessive movement of the whole-body centre of mass relative to the kayak's centre of rotation.

The shoulders and head also actively countered the voluntary kayak movement in Task A, likely to offset the high magnitude of kayak motion. However, during the anticipatory static balance tasks (A and B), these segments exhibited a proportional relationship with kayak orientation (Figure 5 and Figure 6). This suggests that as the trunk maintained a vertical alignment to preserve equilibrium and centre of pressure, any additional excessive oscillations or sudden system movements would prompt head or shoulder-based compensatory strategies.

Table 3: Kayak and segments angle range and magnitude (SD) relationship for three experimental task conditions

		Counter-clockwise angle	Clockwise angle	Range	Magnitude (SD)	(vs. kayak) Angle range ratio	(vs. kayak) Pearson *r*
Kayak		25°	-24°	49 ± 8°	15 ± 3°		
	Pelvis	10°	-12°	22 ± 9°	6 ± 3°	0.5	0.88
	Trunk	6°	-5°	12 ± 4°	3 ± 1°	0.2	-0.71
	Shoulder	11°	-9°	20 ± 12°	5 ± 3°	0.4	-0.08
	Head	9°	-19°	20 ± 10°	5 ± 23°	0.4	0.10
Kayak		7°	-6°	12 ± 10°	3 ± 3°		
	Pelvis	2°	-5°	7 ± 4°	2 ± 1°	0.6	0.64
	Trunk	2°	-2°	4 ± 2°	1 ± 1°	0.3	0.41
	Shoulder	6°	-3°	9 ± 4°	2 ± 1°	0.7	0.74
	Head	7°	-7°	14 ± 7°	3 ± 2°	1.1	0.55
Kayak		8°	-7°	15 ± 9°	4 ± 3°		
	Pelvis	2°	-5°	8 ± 4°	2 ± 1°	0.5	0.77
	Trunk	2°	-2°	4 ± 1°	1 ± 0°	0.3	0.40
	Shoulder	4°	-6°	10 ± 6°	2 ± 2°	0.7	0.65
	Head	5°	-8°	13 ± 8°	3 ± 2°	0.9	0.39

(Correlation coefficient Pearson *r* value: - more than 0.50 and positive - indicates proportional direction of movement; less than 0.50 - corresponds to uncoupling movement; negative - opposite direction of movement (Pozzo et al., 1995)

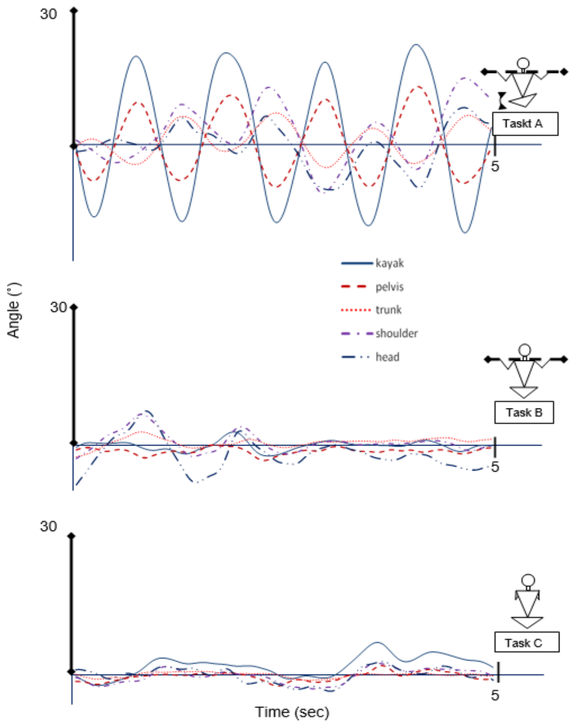


Figure 5: Relationship between body segments and kayak roll angle for a highly experienced participant, shown over a 5-second period across the three experimental conditions

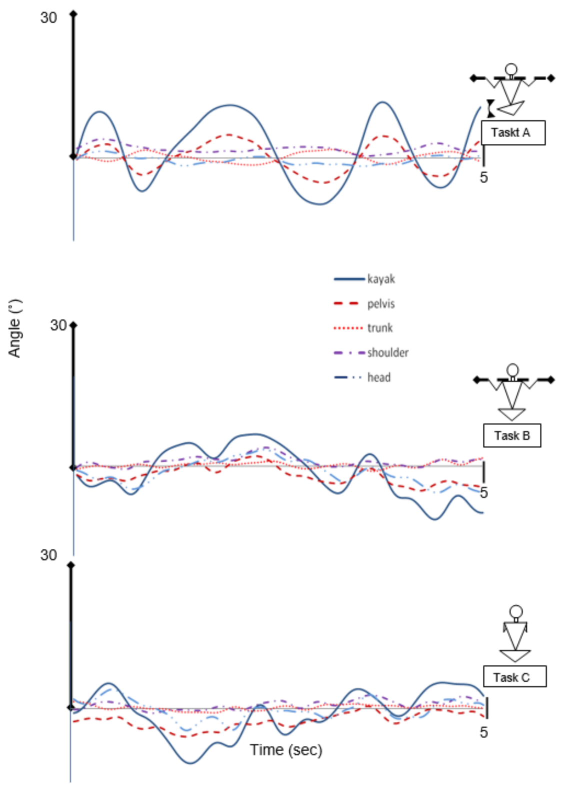


Figure 6: Relationship between body segments and kayak roll angle for a less experienced participant, shown over a 5-second period across the three experimental conditions

DISCUSSION

Kayak motion characteristics

This study sought to establish the kinematic characteristics of the stationary sprint kayak under three different balancing conditions. The results showed that the medial-lateral (sway) and vertical (heave) motion of the kayak were within acceptable ranges of control for each experimental task. As evident in the first condition (Task A), higher translation magnitudes were generated due to the voluntary rolling motion combined with continuous anticipatory postural adjustments by the subjects. Another key characteristic was the asymmetrical translational and rotational motion of the kayak, with most subjects being unable to produce balanced counter-clockwise and clockwise lateral oscillations. This asymmetric balance characteristic would also affect the drift state of the kayak, and could be used to distinguish between kayakers with good stability and those lacking it. For instance, in the more demanding Task C, less experienced participants exhibited high kayak oscillations and sway ranges compared to experienced participants. Furthermore, this unbalanced characteristic was reflected in the higher asymmetrical kayak roll angles produced by the less experienced participants. Due to poor balance control, the less experienced participants failed to initiate sufficient counterbalance action to stabilize the kayak, resulting in it remaining tilted to one side for a period of time. However, the highest maximum kayak roll angle of 30 degrees was proactively produced by an experienced participant in the voluntary rolling condition, and this angle was almost symmetrical on either side for the entire duration of the task.

Segments and kayak motion relationship

As discussed in the previous study, the gravitational and buoyancy forces acting on the kayak-paddler system contribute to unbalanced moments that may lead to excessive kayak rolling or capsizing if not counteracted (Michael et al., 2009; Bonaiuto et al., 2020; Gomes et al., 2017) . The findings from Task A demonstrate how the various body segments were utilized to make appropriate adjustments in order to control the anticipatory and unbalanced motion generated. Furthermore, the results from the static balance experimental conditions suggest that limitations in segment involvement will lead to increased magnitudes of balance control efforts. The findings also suggest that the pelvis was the primary actuator in initiating the oscillatory motion of the stationary kayak. This was evidenced by a consistent and proportional relationship between the angular motion of the pelvis and the kayak's movement. To voluntarily generate lateral rolling of the kayak, participants were required to continuously shift their centre of pressure from one side of the seat to the other while maintaining postural stability. This was accomplished either by alternately pushing the foot-brace with one leg or by continuously shifting both knees laterally through internal and external rotation of the hip joints. In this study, the pelvis segment was used to represent the lower extremity motion. The association between pelvis and hip movement has been reported in previous research as well (Limonta et al., 2010; Brown et al., 2011; Bertozzi et al., 2012; Michael et al., 2009). However, solely analysing the pelvis may not provide a comprehensive understanding of the roles played by the lower limbs in controlling the balance and stability of a sprint kayak.

For complex equilibrium tasks, minimizing the displacement of the body's centre of mass is crucial. Accordingly, upper body movement, particularly trunk displacement, must be limited and remain inclined relative to the vertical (Michael et al., 2009). The findings of the current study demonstrated that the trunk was consistently inclined, as evidenced by the low translational and rotational magnitudes, as well as a proportional movement relationship with kayak motion, especially in Tasks B and C. Furthermore, the trunk angle magnitudes were at a minimum value with a negative correlation, even though additional voluntary oscillation of the kayak was involved in Task A. This result may limit the feasibility of utilizing trunk strategies for stabilization. However, there is a possibility that this strategy may only be effective in controllable balance tasks where the trunk is not employed as an actuator for additional stabilization. The study found that the shoulder and head exhibited greater angular displacements compared to the trunk. Consequently, the participants utilized head and shoulder stabilization strategies to counteract these excessive system oscillations. Specifically, in the voluntary kayak lateral rolling condition, shoulder movements demonstrated a negative correlation with kayak motion, suggesting that the shoulders oscillated in the opposite direction to compensate for the excessive kayak instability. Furthermore, the head tended to remain vertically oriented, serving as a postural reference for control during this task.

CONCLUSION

Balance control in sprint kayaking is a multifaceted skill that requires the assessment and coordination of various body segments. It should not be viewed solely as an automatic reflex response. This study's focus on only the upper body and pelvis segment represents a limitation, as a holistic analysis of the biomechanical quantities of the entire system would provide more comprehensive and accurate insights into the underlying control strategies. Developing balance control in sprint kayaking can be considered an essential skill that can be enhanced through diverse practice and training in varying environmental and task contexts, ultimately leading to more flexible and adaptable competencies. Consistent practice and the utilization of reliable balance training aids can contribute to the improvement of sprint kayak balance control abilities.

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