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Changes of Lower Limb Kinematics during 2000m Ergometer Rowing among Male Junior National Rowers

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ABSTRACT

Rowing involves cyclic motions that have a number of similar repetitions of joint excursion. Similar movement patterns, physiological, muscular activity and biomechanical aspects were observed while rowing on dynamic ergometer and on water. The purpose of our study is to evaluate the changes of lower limb kinematics during 2000m rowing on dynamic ergometer among male junior national rowers. Ten male junior national-level rowers participated in the study. 24 passive reflective markers were attached on their lower extremity and their rowing motions were captured. Each phases of rowing cycle was interpolated to 100 time points separately. The lower limb joint kinematics were compared across every 500m sections to evaluate its changes during 2000m rowing trial. There was a statistically significant difference between stroke rates for every 500m of 2000m rowing trial as determined by one-way ANOVA ($F(3,36) = 4.880$, $p = 0.006$). Kinematical variabilities were observed across splits particularly in frontal and transverse planes of lower limb joints.

Keywords: Biomechanics, kinematics, rowing, youth

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INTRODUCTION

Rowing involves cyclic motions that have a number of similar repetitions of joint excursion (Jürimäe et al., 2010). Cyclic motions are common in sports such as walking, running and cycling. In rowing, the execution begins with catch position, then drive phase, followed by finish position, recovery phase and then returns to the catch position and the cycle repeats. The drive phase begins at the catch position whereby the upper limb is maximally extended while the lower limbs is maximally flexed, and ends with maximum extension of lower limbs and maximum flexion of elbow joint. Then, the finish phase is indicated as the rowers reached to the back of the boat with extended trunk and legs. Next, the recovery phase is the return of the rower from finish position to catch position of following cycle. Successful elite rowers generate power mainly from legs (75-80% of total power) and only about 20-25% of total power was generated from arms (Cosgrove et al., 1999).

There are a number of studies that compared the biomechanical aspects of rowing on ergometer and on-water rowing (Dawson et al., 1998; Fleming et al., 2014; Mello et al., 2009) and across the types of ergometer (Holsgaard-Larsen & Jensen, 2010; Benson et al., 2011; Shaharudin et al., 2014a). There are two types of ergometer that are commonly used by rowers; dynamic and stationary ergometer. Dynamic ergometer consists of two sliders that were mounted underneath a stationary ergometer. Several authors have previously showed that rowing on dynamic ergometer may better simulate movement patterns associated with on-water rowing (Bernstein et al., 2002; Colloud et al., 2006; Elliott et al., 2002). Furthermore, similar physiological (e.g. heart rate, oxygen consumption and blood lactate concentration) (Benson et al., 2011; Mahony et al., 1999), muscular activity (Fleming et al., 2014) and biomechanical aspects (Dawson et al., 1998; Lamb, 1989) were observed while rowing on dynamic ergometer and on water.

However, Fohanno et al. (2015) found that rowing on dynamic ergometer might increase risk of injury due to increased load on lower limb joints to overcome inertial mass during catch. More precisely, rowers are dependent on their lower limb to exert forces on the foot stretchers (Kleshnev, 2007). Hence, the asymmetry of leg length and force generated at the foot stretcher may cause lower back imbalances and further increase lumbar pain (Janshen et al., 2009). Furthermore, rowers need to aim for maximum power output and it may result in asymmetrical or adverse body mechanics while rowing on ergometer compared to on-water rowing (Torres-Moreno et al., 2000).

According to Kingma et al. (1998), rowing stroke is advocated to move with symmetrically coordinated movements to minimise torsional force and tendency for low back pain. Moreover, executing the rowing stroke with asymmetrical lower limb motion may result in compensatory pelvic motions and contractions of trunk stabilisers muscles (e.g., transverses abdominis and erector spinae) and thus, influencing the action of the spine (Buckeridge et al., 2012). Fatigue causes changes in rowing technique, such as changing the timing of coordination between body segments (Holt et al., 2003; McGregor et al., 2005). Pollock et al. (2012) found that a change in the timing of leg drive, trunk extension, and arm pull execution might also influence the coordination of the pelvic and spinal segments. For example, during the final sprint of 2000m race, the trunk has to generate greater force to compensate for the power loss from knee extension. Hence, the purpose of our study is to evaluate the changes of lower limb kinematics during 2000m rowing on dynamic ergometer among male junior national rowers. The findings from this study may provide insights in rowing technique modification and enhancement.

METHODOLOGY

Recruitment of Participants

Participants were recruited voluntary through national coach. Ten male junior national-level rowers participated in the study. Rowers of age 13 – 17 years old with no serious musculoskeletal injuries within the past year were included in the study. Consent was obtained from the participants and their guardians. The study protocol was reviewed and approved by Human Research Ethical Committee of Universiti Sains Malaysia (USM/JEPeM/15020080). The research was conducted in compliance to Declaration of Helsinki 1975.

Study Protocol

Participants underwent a physical check-up, which included the evaluation of weight, height, body circumference (i.e., hip, waist and thigh) and body segment length (i.e., shank and thigh). Shank is the part of the lower limb between the knee and the ankle, while thigh is the part of the lower limb between the hip and the knee. Standing height and body weight were measured using Seca Stadiometer (Model 224, Germany). During measuring standing height, participants were instructed to take a deep breath for measuring actual standing height respectively. Then, the body mass index (BMI) of each participant was calculated by division of body weight (in kilograms) over standing height squared (in centimetres). The shank-thigh length ratio was measured based on the markers attachment by using anthropometrical tape. The length of thigh was measured from greater trochanter marker to lateral epicondyle marker while the length of shank was measured from lateral epicondyle marker to lateral prominence of lateral malleolus marker. Hence, shank-thigh ratio was determined by the length of shank divided with the length of thigh.

Then, participants were asked to provide information about their medical history and any medications taking. Participants were advised to wear fitting clothes for accurate marker placement on the body. Prior to the test day, they needed to have at least six hours of sleep. They also needed to take a light meal before coming for the test. Next, 24 passive reflective markers (model hard marker 15mm, QUALISYS AB, Sweden) were attached on both sides of anterior superior iliac spine anterior superior iliac spine, both sides of anterior superior iliac spine posterior superior iliac spine, both sides of anterior superior iliac spine greater trochanter, both sides of anterior superior iliac spine femoral wand, both sides of anterior superior iliac spine lateral epicondyle, both sides of anterior superior iliac spine medial epicondyle, both sides of anterior superior iliac spine tibial tubercle, right and left lateral malleolus, both sides of anterior superior iliac spine medial malleolus, both sides of anterior superior iliac spine calcaneous, both sides of anterior superior iliac spine second metatarsal head and both sides of anterior superior iliac spine fifth metatarsal head. One passive reflective marker was attached on the posterior part of ergometer. Correct positions of the markers were the key factor in achieving a good quality of motion capture.

After markers attachment, the participants stood stationary to capture the full-body static pose. Participants were notified to stand in the anatomical position with both upper limbs open a bit to the side with lower limbs were positioned with shoulder-width apart. The static pose was captured for two seconds. Then, four reflective markers were removed prior to the rowing trial once the static pose was captured. All the four markers were located on the medial anatomical landmarks which include right and left medial epicondyle and right and left medial malleolus. The markers were removed for the ease and smoothness of rowing motion. Another 20 markers on the selected anatomical landmarks and one marker on the ergometer remained.

Next, all participants went through similar 2000m rowing test on dynamic Concept 2, Model D ergometer (Concept 2 Inc., Morrisville, VT). Participants were asked to perform warm up for two to three minutes with no workload and resistance followed by a minute of active rest. After that, standardized drag factor (e.g., resistance) referred from Australian Rowing Team Ergometer Protocols was added according to the body weight of participants. The tests began once the participant was ready. During the test, the 3D motion was captured for ten consecutive rowing strokes at every 500m split during 2000m rowing. Verbal encouragement was provided during the test. The time to completion was recorded after the participant reached 2000m of rowing.

Finally, the trajectory of reflective markers that were captured previously was identified using QTM software (QUALISYS AB, Sweden) to build a musculoskeletal modelling. Each marker was identified according to the acronym names of the anatomical landmarks. After the identification of markers was completed, the motion captured was further analysed using Visual3D Standard v4.90.0 (Gothenburg, Sweden) to create musculoskeletal model which allowed detailed analysis of coordination.

Once the markers identification was done, data from QTM software were exported to Microsoft Office Excel (Microsoft Corporation, 2007). A set of ten consecutive stroke cycles was extracted and averaged to obtain a representative pattern for each 500m of 2000m rowing test. Then, the rowing phases were defined through the analysis of position and orientation of the wrist joint marker projected along the longitudinal axis of the ergometer (Shaharudin et al., 2015; Shaharudin et al., 2014b). The drive phase ranged from 0 to 100% and the recovery phase from -100 to 0% (Pollock et al., 2009). Each phases of rowing cycle (e.g., drive and recovery) was interpolated to 100 time points separately following technique by (Pollock et al., 2012). Therefore, the complete stroke was composed of 200 time-points. The interpolation technique is crucial to allow comparison across rowing phases and participants (Pollock et al., 2012). The interpolation and graphs were created by using MATLAB (R2014b, version 8.3, The MathWorks, Inc., US) software. Next, the lower extremity joint kinematics was compared across the four data points (i.e., ten strokes for every 500m) to evaluate its changes during 2000m rowing trial.

Statistical Analysis

All the statistical tests were analysed using IBM SPSS (Statistical Product and Service Solutions) statistics software version 23 (International Business Machines Corporation, United States). Significance value was set at $\alpha = 0.05$. The descriptive statistics were applied on the anthropometric data and rowing performance. All data were expressed as mean ± standard deviation (SD). The Kolmogorov-Smirnov test was employed to determine the normality of the data.

Table 1

Physical characteristics of participants (N=10)

Physical characteristics	Mean ± SD
Age (years)	16.4 ± 0.5
Height (m)	1.73 ± 0.05
Weight (kg)	70.2 ± 9.2
BMI (kg/m^2)	23.44 ± 2.67
Hip circumference (cm)	97.9 ± 12.2
Thigh circumference (cm)	42.3 ± 2.45
Shank length (m)	0.43 ± 0.03
Thigh length (m)	0.49 ± 0.04
Shank to Thigh Ratio	0.9 ± 0.1

RESULTS

Physical Characteristics of Participants

The descriptive statistics were applied to assess participants' physical characteristics (Table 1).

Rowing Performance on Dynamic Ergometer

Rowing performance on dynamic ergometer data of all participants were presented in Table 2.

There was a statistically significant difference between stroke rates for every 500m split of 2000m rowing distance as determined by one-way ANOVA (F(3,36) = 4.880, *p* = 0.006) (Table 2). A Tukey's honestly significant difference (HSD) post hoc test revealed that there were significant differences of stroke rates between 500m section and 2000m section splits (*p* = 0.044), between 1000m section and 2000m section splits (*p* = 0.013), and between 1500m section and 2000 section splits (*p* = 0.013).

Table 2

Rowing performance on dynamic ergometer (N=10)

Rowing performance	Mean ± SD
Time to completion (min)	7.57 ± 0.42
Stroke per minute (spm)	
500m	32.2 ± 3.2
1000m	31.2 ± 3.2
1500m	31.2 ± 2.7
2000m	37.6 ± 7.0

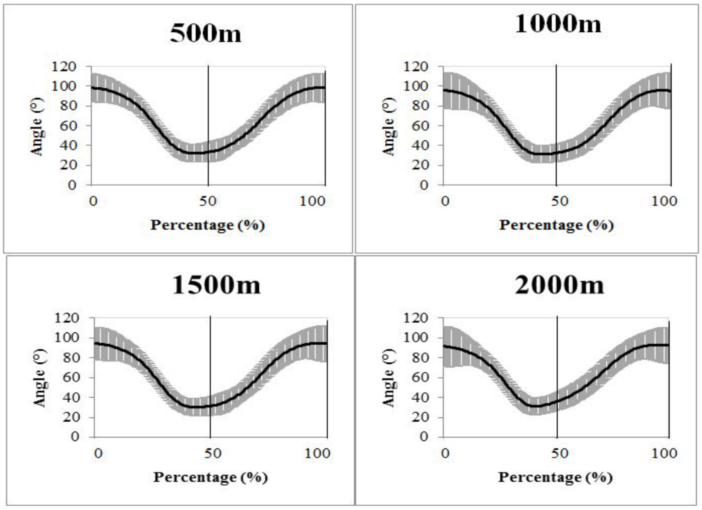

Figure 1. Changes of hip joint angle in sagittal plane across 2000m time trial rowing on dynamic ergometer. 0% to 50% indicates recovery phase while 50%-100% indicates drive phase.

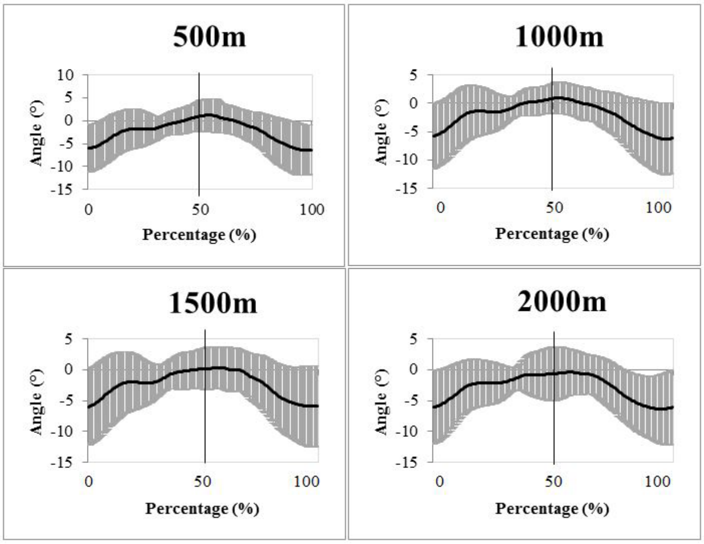

Figure 2. Changes of hip joint angle in frontal plane across 2000m time trial rowing on dynamic ergometer. Positive angle indicates adduction while negative angle indicates abduction. 0% to 50% indicates recovery phase while 50%-100% indicates drive phase.

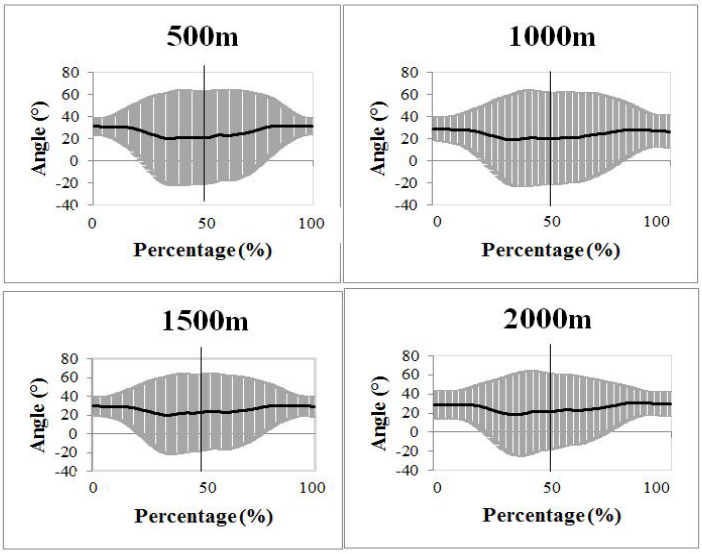

Figure 3. Changes of hip joint angle in transverse plane across 2000m time trial rowing on dynamic ergometer. Positive angle indicates internal rotation while negative angle indicates external rotation. 0% to 50% indicates recovery phase while 50%-100% indicates drive phase.

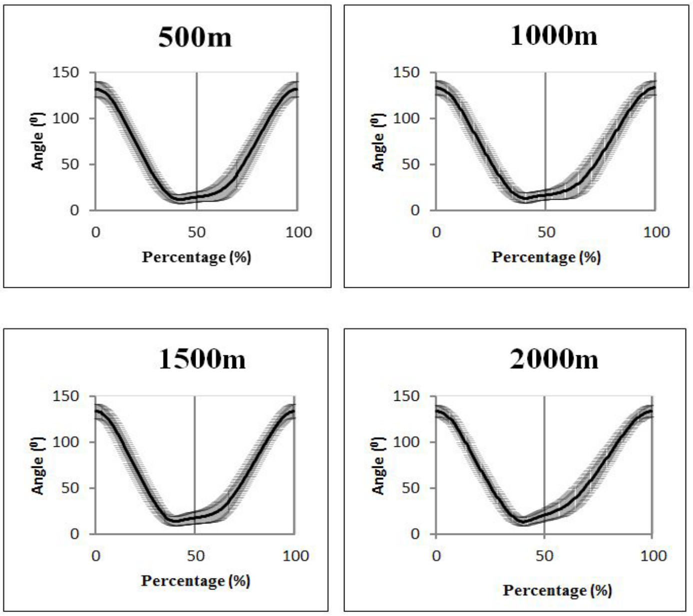

Figure 4. Changes of knee joint angle in sagittal plane across 2000m time trial rowing on dynamic ergometer. Increment of angle indicates knee extension and decrement of angle indicates knee flexion. 0% to 50% indicates recovery phase while 50%-100% indicates drive phase.

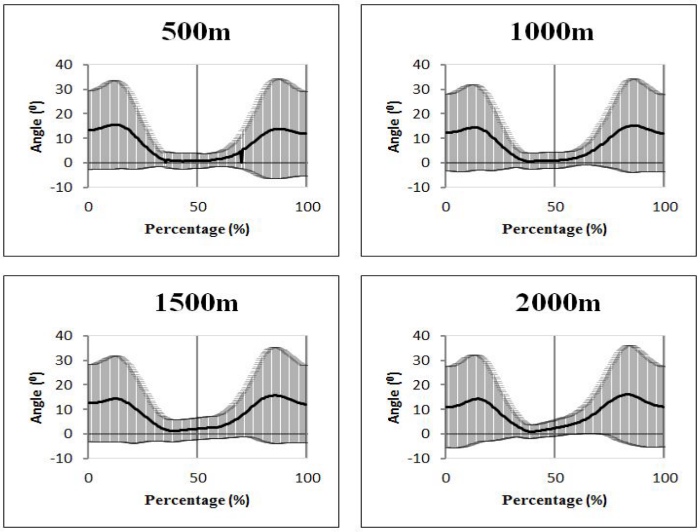

Figure 5. Changes of knee joint angle in frontal plane across 2000m time trial rowing on dynamic ergometer. Increment of angle indicates knee adduction and decrement of angle indicates knee abduction. 0% to 50% indicates recovery phase while 50%-100% indicates drive phase.

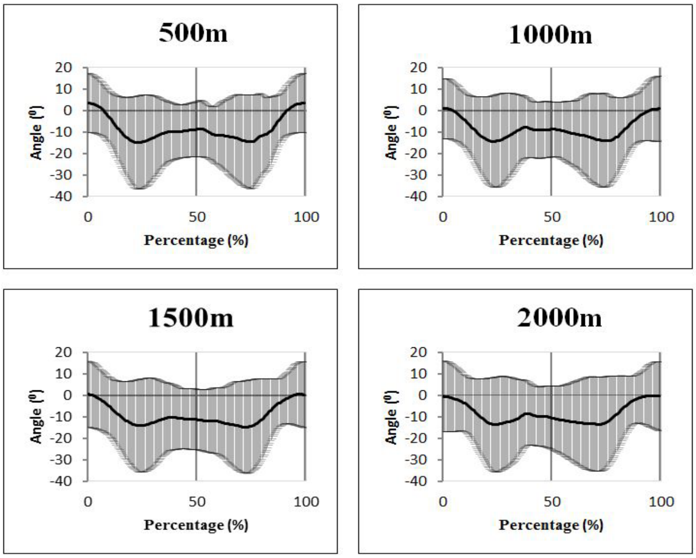

Figure 6. Changes of relative knee joint angle in transverse plane across 2000m time trial rowing on dynamic ergometer. 0% to 50% indicates recovery phase while 50%-100% indicates drive phase.

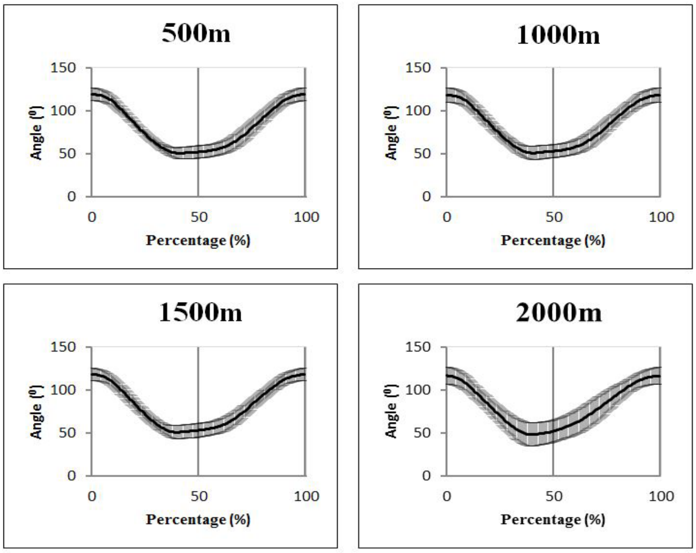

Figure 7. Changes of ankle joint relative angle in sagittal plane across 2000m time trial rowing on dynamic ergometer. 0% to 50% indicates recovery phase while 50% to 100% indicates drive phase.

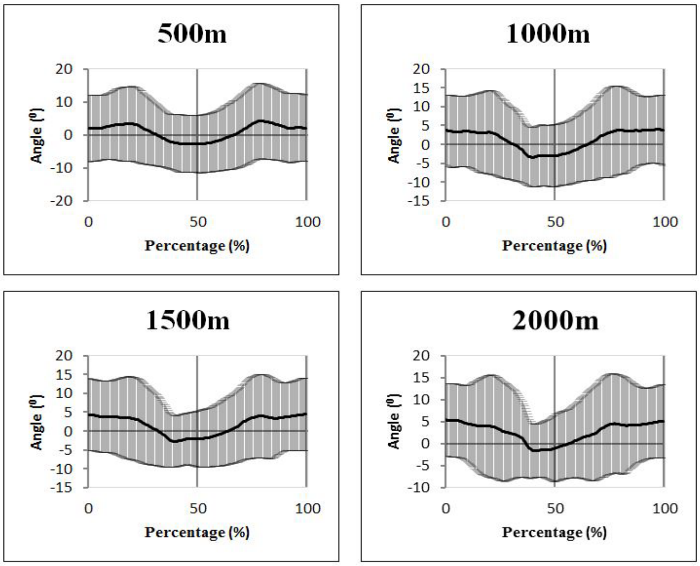

Figure 8. Changes of ankle joint relative angle in frontal plane across 2000m time trial rowing on dynamic ergometer. 0% to 50% indicates recovery phase while 50% to 100% indicates drive phase.

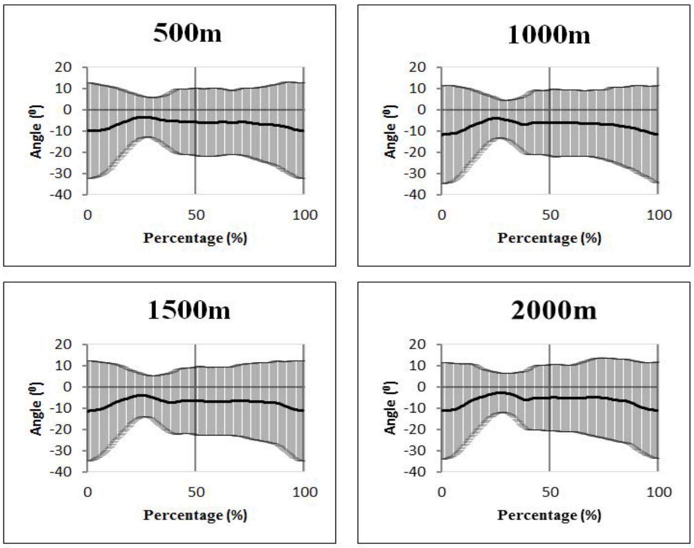

Figure 9. Changes of ankle joint relative angle in transverse plane across 2000m time trial rowing on dynamic ergometer. 0% to 50% indicates recovery phase while 50% to 100% indicates drive phase.

Ensemble Averages of Lower Limb Kinematics

Hip, knee and ankle joints angles in sagittal, frontal and transverse planes were evaluated for every 500m of 2000m rowing distance (Figure 1-9). The ensemble averages consisted of drive (from 0% to 50%) and recovery (from 50% to 100%) phases.

DISCUSSION

Our participants recorded 7.57 ± 0.42 min for 2000m ergometer rowing time trial which considered slow than 6.37 ± 0.08 min recorded in Australian male junior rowers (Lawton et al., 2012). The stroke rate was slightly fluctuated from 500m to 1500m splits and finished with the highest stroke rate. The consistency of stroke rates between 500m and 1500m enabled rowers to generate high stroke power at the last 500m split. The high stroke rates resulted in a shorter time to completion. Stroke rate and velocity are directly related whereby high stroke rate would increase the boat velocity (Soper & Hume, 2004). Previous studies showed negative correlation between stroke rate and stroke length (Fritzdorf et al., 2009; Thompson et al., 2000). As our rowers are shorter than rowers from previous studies (Mikulić, 2008; Soper & Hume, 2004), perhaps increasing stroke rates was a strategy to increase boat velocity.

The main objective of the study was to evaluate the changes of lower limb kinematics during dynamic ergometer rowing. To the best of our knowledge, studies regarding the changes of lower limb joints kinematics during dynamic ergometer rowing were scarce.

Figure 1 showed the flexion/extension movement of hip joint in sagittal plane. Figure 2 showed the adduction/abduction movement of hip joint in frontal plane. The hip was adducted during at the end of drive phase and at the beginning of recovery phase then abducted during the beginning of drive phase and at the end of recovery phase. Figure 3 showed the internal/external rotation movement of hip joint in transverse plane. The hip was internally rotated during the beginning of drive phase and at the end of recovery phase and then externally rotated during at the end of drive phase and at the beginning of recovery phase. The high variability in frontal and transverse planes is probably due to the leg alignment that we did not measure. Besides, due to sitting position on ergometer, fewer changes in hip motions were observed except at sagittal plane.

For knee kinematic in sagittal plane (Figure 4), the participants showed maximum knee flexion during catch position and maximum knee extension during finish position throughout the four sections (e.g., 500m, 1000m, 1500m and 2000m). There was a plateau at the transition between drive and recovery phase whereby the participants rode the momentum at finish position before continue to the catch position. Knee pain is common in rowers (Hosea & Hannafin, 2012; Karlson, 2012; Smoljanovic et al., 2015). Excessive knee flexion during rowing places high compressive forces between the posterior of the patella and the femur (Waryasz et al., 2016). Furthermore, abnormal tracking of the patella often leads to an imbalance of forces around the joint (Thornton et al., 2017).

For knee kinematic in frontal plane (Figure 5), our results showed that the knee joint was always in adducted position whereby the knees moved toward to the midline of the body for all sections. The motion was observed during the middle of drive phase until finish position. This finding is similar to Waryasz et al. (2016) whereby the rowers experienced a "knock-kneed" appearance through drive phase because of a genu valgum dysfunction or adductor moment of the femur. However, rowers with an increased abduction moment or "bow legs" may develop iliotibial band syndrome which is an irritation due to increased compression of the iliotibial band over the lateral femoral condyle (Fairclough et al., 2006). Thus, specific assessment of lower limb alignment is important to assess for rowers before the start of rowing session to avoid any knee injury that would be detrimental for performance.

For knee kinematic in transverse plane (Figure 6), external rotation was observed at the early of drive phase until the middle of drive phase, whereas, internal rotation were identified at the middle of recovery phase and ended at the late of recovery phase. In addition, during the first 500m, the knee was in internal rotation during catch position. However, the motion changed across the next three splits (e.g., 1000m, 1500m and 2000m) whereby the knee joint was in neutral position. These events showed that participants were struggling at first to adapt while generating strokes on dynamic ergometer. Hence, it was shown that at catch position (50%), the knees flexed, adduct and internally rotated while at finish position (0% and 100%) the knees extended, abduct and externally rotated.

Figure 7 depicted the movement of ankle joint in sagittal plane which was consistent across all 2000m time trial. However, the variability of ankle joint movement patterns increased as the participants rowed toward the time trial completion. At 2000m section, there was high variability begins from the middle of drive phase until the middle of recovery phase. This variability could be due to increased power production at the foot and high stroke rates. In a muscle activity study, it was shown that the gastrocnemius lateralis (GL) muscle was the earliest to activate, as plantar flexion was used prominently in the drive phase of rowing which GL enabled force transfer from the foot stretcher to the thigh muscles (Gerževič et al., 2011; Jürimäe et al., 2010). Hence, ankle joint motions in sagittal plane are important for force transfer from distal to proximal parts of lower limb.

Ankle joint motions in frontal plane showed high variability across all sections especially during the middle of drive phase (Figure 8). The ankle joint inverts during early to middle drive phase and during middle until end of recovery phase. Then, the ankle joint everts during the middle of drive phase until the middle of recovery phase. The position of ankle joint was consistently externally rotated across every studied splits (Figure 9). However, there was slight movement of ankle internal and external rotation during early and middle of drive phase.

Based on the figures, we observed that during the drive phase, as the knee joint abducted, the knee also externally rotated. For the ankle joint, eversion-internal rotation coupling motion was also observed during drive phase. Then, the *vice versa* occurred during recovery phase whereby the knee joint adducted and internally rotated while the ankle joint inverted and externally rotated. Hence, following the kinetic chain concept, it was noted that movement in rowing at a specific joint may affect its neighbouring joints and segments.

Limitation

Dynamic ergometer design underestimated the kinetic energy which is required to accelerate the rower's centre of mass during on-water rowing as stroke rate and exercise intensity increased (Fleming et al., 2014). Particularly, muscles activities were markedly greater at early drive and recovery phase during on-water than dynamic ergometer rowing (Fleming et al., 2014). This is because rowing ergometers are more stable than on-water rowing hence, additional activation of stabilising muscles may not be necessary. Furthermore, some studies have found differences in arm motion (Lamb, 1989), handle force and acceleration profiles (Kleshnev, 2005) between ergometer and on-water rowing performance. However, these variables were not included in the current study.

CONCLUSIONS

Variabilities were observed particularly in frontal and transverse planes of lower limb joints. Knee and ankle motion of internal/external rotation are important for rowers to stabilise their body especially during the end of drive phase or in the position of finish. Early detection of the false technique is important to improve rowing performance because false technique increases risk of injury (Thornton et al., 2017).

PRACTICAL APPLICATION

Specific assessment of lower limb alignment is important to assess rowers prior to rowing season to avoid any injury that would be detrimental to performance.

CONFLICTS OF INTEREST

There are no conflicts of interest to declare.

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