Journal of Physical Education and Sport ® (JPES), Vol.19 (3), Art 240 pp. 1656 - 1662, 2019
online ISSN: 2247 - 806X; p-ISSN: 2247 – 8051; ISSN - L = 2247 - 8051 © JPES

Original Article

Changes in lower limb kinematics coordination during 2000m ergometer rowing among male junior national rowers

FARA LIANA ZAINUDDIN[1], AMIRAH ZAHIRAN[2], MUHAMMAD AIMAN UMAR[3], SHAZLIN SHAHARUDIN[4], RIZAL MOHD RAZMAN[5]
[1,2,3,4]Exercise & Sports Science Programme, School of Health Sciences, Universiti Sains Malaysia, MALAYSIA
[5]Sports Centre, University of Malaya, MALAYSIA

(Accepted for publication: August 28, 2019)
DOI:10.7752/jpes.2019.03240

Abstract:
Joint coordination is important for rowers because a non-optimal strategy may limit the power output and movement efficiency during rowing. Although lower limb joint coordination is fundamental during rowing, studies on this aspect, particularly during ergometer rowing, are scarce. The purpose of this study was to evaluate the changes of lower limb kinematics coordination during a 2000m timetrial on a dynamic rowing ergometer. Ten male junior national rowers were recruited. Three-dimensional lower limb kinematics were captured and recorded for ten strokes for every 500m splits of 2000m time trial using nine high-speed infrared cameras. Then, Principal Component Analysis (PCA) was applied to determine the coordination coefficients that represented the temporal activity of the coordination and coordination vectors corresponding to the relative weightings of each kinematic variable within the coordination. The rowers completed 2000m timetrial in 7.57 ± 0.42 minutes. To the best of our knowledge, this was the first study that evaluated joint coordination during 500m splits of 2000m rowing time trial among trained rowers. Joint coordination of lower limb kinematics could be distinguished in two robust factors that were consistent across 500m splits of 2000m rowing time trial. Main coordination was contributed by hip joint in all planes, knee joint in the sagittal and frontal planes, and ankle joint in the sagittal and transverse planes. Meanwhile, minor coordination was comprised of knee joint in the transverse plane and ankle joint in the frontal plane.There were small changes in the loading vectors for both factors across the time trial. Coaches and rowers may emphasize their training on the specific joint movement that contributes to the main coordination. This strategy may enhance their rowing performance and joint coordination.
Keywords*:* coordination,factor analysis, rowing, synergy, youth

Introduction

Rowing emphasizes coordinated movement in which it requires perfect synchronization between rowers in a boat and within a rower themselves (e.g., inter-joint coordination). The degree of synchronization is an important determinant for optimal crew performance, which may increase the chances of winning (Hill, 2002; Shaharudin & Agrawal, 2016). Furthermore, it has been shown that an uncoordinated movement can hinder performance even within a team of strong and technically-proficient rowers (Cuijpers et al., 2015). Intra crew coordination is known as phase coordination, which is classified as in-phase and antiphase coordination that affect the crew's rowing performance. In-phase coordination is recognized when the rhythmic hand motions perfectly coincide among rowing crew,while antiphase coordination is observed when the rhythmic motions alternate each other with a half-a-cycle difference (Cuijpers et al., 2015).

On the other hand, coordination within a rower encompasses joint and time coordination. The joint coordination is important for applying a skill that requires the transfer of force generatedthrough a kinetic chain of multi-joint movement. Furthermore, Heiderscheit et al., (2002) have reported that the combination of joint coordination variability and task outcome consistency has been frequently demonstrated. For example, proper coordination of whole-body segments and joints may help a baseball player to execute a good pitching skill (Chen et al., 2016). Wilson et al., (2008) have also observed that the coordination of lower extremity intra-limb couplings may influence the skill of expert triple jumpers. Meanwhile, time coordination is defined as the changes in time coordination between body segments over a sustained period, which are frequently attributed to fatigue (Caldwell et al., 2003; Holt et al., 2003; McGregor et al., 2005). The time coordination is crucial particularly for sports that determine the winner based on the fastest time recorded. Despite the importance of joint and time coordination on rowing performance, studies related to these aspects are scarce.

Development of effective coordination between upper and lower limb is crucial for rowers because non-optimal strategiesmay limit their movement efficiency and power output (Hug et al., 2011). It is well-known that lower limb musculature is the main propulsive force generator during rowing (Shaharudin et al., 2014;

Corresponding Author: SHAZLIN SHAHARUDIN, E-mail: shazlin@usm.my

Shaharudin & Agrawal, 2016). Although lower limb joint coordination is fundamental during rowing, studies on this aspect, particularly during ergometer rowing, are scarce. Hence, the purpose of the present study was to investigate the changes of lower limb joint coordination, which were analyzed using factor analysis of its kinematics across 2000m ergometer rowing time trial among male rowers.

Material & methods

Participants

Ten male junior national-level rowers participated voluntarily in the study. Rowers aged 13 – 17 years old with no serious musculoskeletal injuries within the past year were included in the study. They trained regularly and had at least one year of experience representing Malaysia at international games. This is important because experience may influence their rowing performance (Penichet-Tomas et al., 2016). Consent was obtained from the participants and their guardians. The study protocol was approved by the Human Research Ethical Committee of a local university (USM/JEPeM/15020080). The research was conducted in compliance with the Declaration of Helsinki.

Study Procedure

Participants were asked to provide information about their medical history and any medications they might be taking. They were advised to wear fitted clothes for ease of rowing motions and accurate marker placement on the body. Participants underwent a physical check-up, which included the measurement of their body weight, height, segments' length (i.e., shank and thigh), and hip, waist and thigh circumference. Standing height and body weight were measured using SecaStadiometer (Model 224, Germany). The length of the thigh was measured from the level of greater trochanter to lateral epicondyle, while the length of shank was measured from the level of lateral epicondyle to lateral malleolus. The shank-thigh ratio was determined by the length of shank divided by the length of thigh (Greene et al., 2009).

Next, 24 reflective markers (model hard marker 15mm, QUALISYS AB, Sweden) were attached on both sides of the anterior superior iliac spine, posterior superior iliac spine, greater trochanter, lateral epicondyle, medial epicondyle, tibial tubercle, lateral malleolus, medial malleolus, calcaneus, second metatarsal head and fifth metatarsal head.Then, the participants stood in the anatomical standing position with the shoulder-width apart while both upper limbs were on their sides. The static pose was captured for two seconds. Then, four reflective markers located on the medial anatomical landmarks, which included both sides of the medial epicondyle and medial malleolus were removed prior to the rowing trial. These medial markers were removed for the smoothness of rowing motion while the remaining 20 markers on the selected anatomical landmarks were left intact.

Next, participants warmed up for two to three minutes by rowing on a dynamic ergometer (Model D, Concept 2 Inc., Morrisville, VT) with a preferred resistance followed by a minute of active rest. After that, the standard drag factor (i.e., resistance) referring to the Australian Rowing Team Ergometer Protocols was added according to the body weight of the participants. During the 2000m time trial, the three-dimensional (3D) motion was captured for ten consecutive rowing strokes at every 500m splits (Greene et al., 2009). Verbal encouragement was provided during the test session (Majumdar et al., 2017). The time to completion was recorded after the participants reached 2000m. The trajectory of reflective markers was identified using the QTM software (QUALISYS AB, Sweden), according to the acronym of the anatomical landmarks. After the identification of markers was completed, the motion captured was further analyzed using Visual3D Standard v4.90.0 (Gothenburg, Sweden) to create a musculoskeletal model that allowed a detailed analysis of lower limb coordination.

Statistical analysis

The adequacy of the dataset for Principal Component Analysis (PCA) was verified with Bartlett's and Kaiser-Meyer Olsen (KMO) tests (Ivanenko et al., 2004). A value greater than 0.6 for the KMO test indicated good sampling size for PCA (Kaiser, 1974; Kline, 1994). PCA with varimax rotation was applied using IBM SPSS version 23 to decompose the lower limb kinematics during each 500m splits of 2000m rowing time trial into a set of one-dimensional principal movements that can be quantified and analyzed independently. PCA was applied to three planes of the knee, hip and ankle which means, six motions were simultaneously analyzed using PCA to identify the underlying factors, thus termed as joint coordination. Only factors with eigenvalues greater than 1 and those that occurred before the inflection point of the scree plot were retained to ensure the robustness of the number of factors obtained from PCA (Kaiser, 1974; Cattell, 1966). Joints with factor loadings greater than 0.55 were considered as contributors for a specific factor (Comrey& Lee, 1992).

The procedure for PCA was done following the methods by Shaharudin et al., (2014, 2015, 2016) on the muscle synergies of untrained and collegiate rowers. Previous kinematic coordination studies in weightlifting (Kipp& Harris, 2015) and triple jump (Wilson et al., 2009) have also applied PCA to investigate joint coordination in different tasks. Results from PCA consisted of two components, (i) "coordination coefficients" that represented the temporal activity of the coordination; and (ii) "coordination vectors" that corresponded to the relative weightings of each kinematic variable within the coordination (Ivanenko et al., 2004). In this study, both components from PCA were compared across 500m splits during the 2000m rowing time trial.

Results The physical characteristics of the rowers are presented in Table 1. They completed the 2000m timetrial in 7.57 ± 0.42 minutes with an average stroke rate of 33.05 ± 4.03 strokes per minute.

Table 1 Physical characteristics of participants, mean ± SD, (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

Data were shown in mean ± SD. m, meter; kg, kilogram; cm, centimeter.

Results from Bartlett's Test of Sphericity on each participant verified that the correlation matrix significantly diverged from the identity matrix ($p < 0.001$), suggesting that the factors were not overlapping with each other. Kline (1994) suggested for the KMO statistic to reach a minimum of 0.6 in order to indicate that the data were sufficient for PCA with varimax rotation. Then, Kaiser's criterion, scree plot and more than 90% of variance accounted for (VAF) indicated that two-factorswere extracted. We defined these factors as joint coordination. The total VAF indicates the variability in the data that can be modeled by the extracted factors, which means that, two factors are sufficient to reproduce joint movement patterns for rowers for every 500m splits of 2000m rowing timetrial as seen in Table 2.

Table 2 Total Variance Accounted For (VAF) for every 500m splits of 2000m rowing time trial (N=10)

	VAF 1	VAF 2	Total VAF
500m	74.4 ± 4.8	17.7 ± 3.7	92.0 ± 2.8
1000m	70.9 ± 9.6	18.3 ± 5.4	89.3 ± 5.8
1500m	72.8 ± 9.3	19.4 ± 6.2	88.3 ± 4.2
2000m	72.6 ± 9.9	16.8 ± 6.8	89.4 ± 4.1

Data were shown in mean ± SD

Coordination activation coefficients were averaged across all participants for the two extracted coordination and expressed as a percentage of the rowing cycle (Shaharudin et al., 2016; Turpin et al., 2011). The joint coordination factor loadings were averaged across all participants for the two extracted coordination. The joint kinematics with factor loadings greater than 0.55 were considered as contributors for a specific coefficient. Each factor is explained by a coordination activation coefficient (i.e., the time-variant component) (Figure 1) and factor loadings of joint kinematics (Figure 2) that contribute to each factor. Most of the joint kinematics were loaded only on one factor which fulfilled the simple structure requirement (Tabachnick&Fidell, 2007).

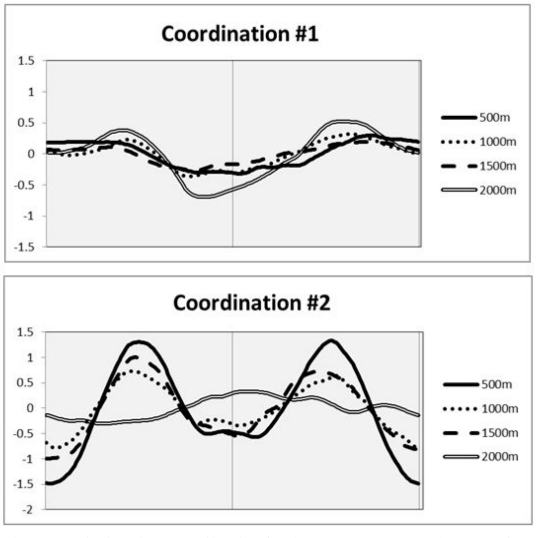
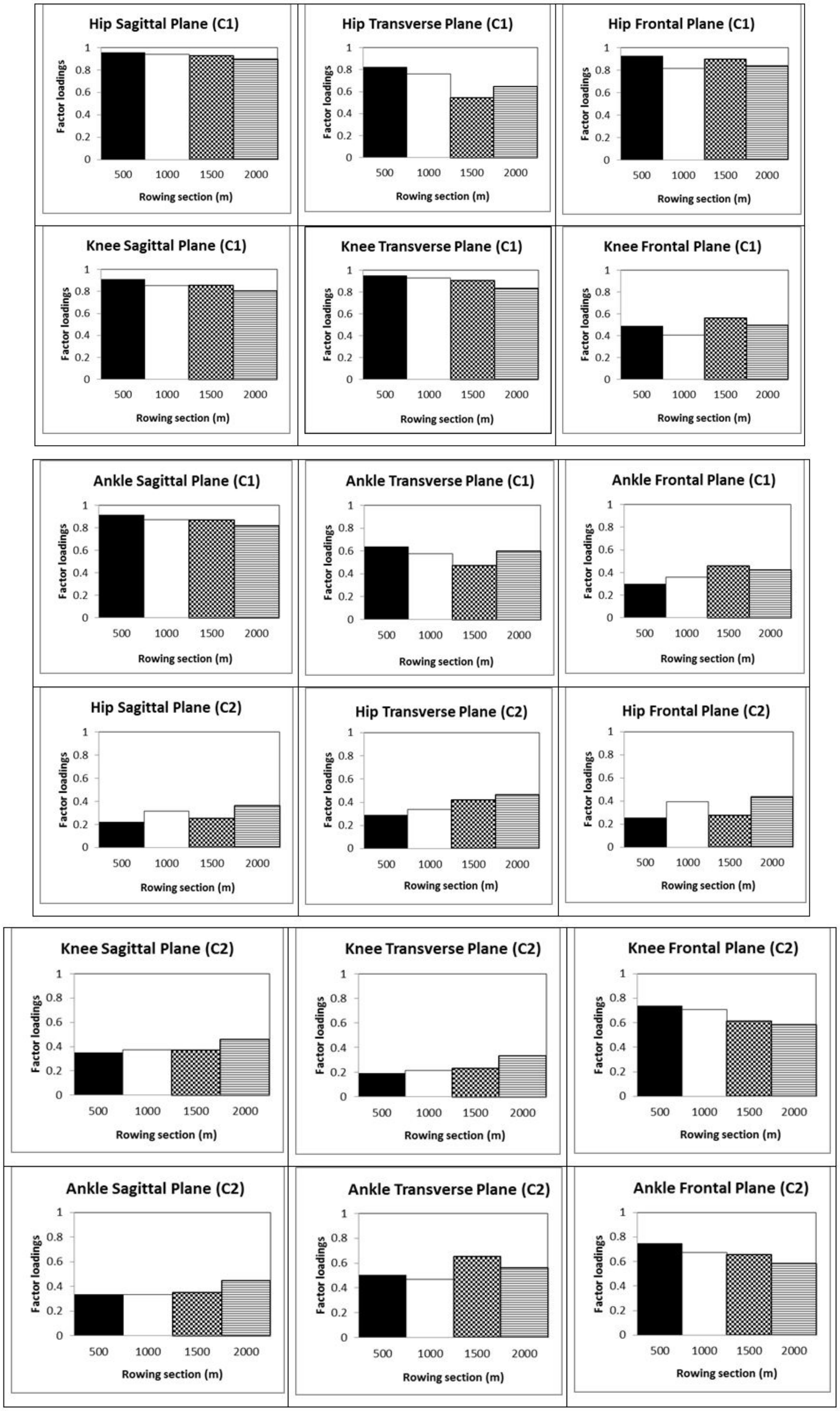


Figure 1 Time-variant coefficients of the lower limb during 500m sections of 2000m time trial. Time-variant coefficients were averaged across rowers for the two extracted coordination and expressed as a function of percentage of a rowing cycle (0% to 50% represents drive phase and 51% to 100% represents recovery phase).



Hip Sagittal Plane (C1)
Hip Transverse Plane (C1)
Hip Frontal Plane (C1)
Knee Sagittal Plane (C1)
Knee Transverse Plane (C1)
Knee Frontal Plane (C1)
Ankle Sagittal Plane (C1)
Ankle Transverse Plane (C1)
Ankle Frontal Plane (C1)
Hip Sagittal Plane (C2)
Hip Transverse Plane (C2)
Hip Frontal Plane (C2)
Knee Sagittal Plane (C2)
Knee Transverse Plane (C2)
Knee Frontal Plane (C2)
Ankle Sagittal Plane (C2)
Ankle Transverse Plane (C2)
Ankle Frontal Plane (C2)

Figure 2 Loading vectors of lower limb coordination during 500m sections of 2000m time trial. The loading vectors were averaged across participants for two extracted coordination. Individual kinematic weightings were depicted for each joint within each coordination. Only kinematic weightings greater than 0.55 were considered as contributors for specific coordination. C1 = coordination #1, C2 = coordination #2.

Discussion

Joint coordination of lower limb kinematics could be distinguished in two robust factors which were consistent across 500m splits of 2000m of the rowing time trial. The factors extracted from PCA were proposed to represent motor programs for a group of joints that performed a specific function during motion (Ivanenko et al., 2004). Extracted coordination consisted of two parts namely the time-variant coefficient and factor loading (Ivanenko et al., 2004). The time-variant coefficients were averaged across all participants for the two extracted coordination and expressed as a function of percentage of the rowing cycle. Meanwhile, factor loading contributed to joint angles with factor loadings greater than 0.55 being considered as contributors for a specific factor. Figures 1 and 2 present the results of coordination activation coefficients and joint coordination factor loadings for every 500m sections of 2000m time trial ergometer rowing. Joint movements showed appreciable loadings and most of the joint movements were loaded only on one factor which fulfilled the requirements for simple structure.

Fatigue causes changes in rowing technique, such as changing the timing of coordination between body segments (Holt et al., 2003; McGregor et al., 2005). A change in the timing of leg drive, trunk extension and arm pull execution may also influence the coordination of the pelvic and spinal segments during rowing (Pollock et al., 2012). The altered kinematics may be related to the adopted motor control strategies in an attempt to maintain power. It has been shown that the trunk is used more actively to generate force as a compensation for the power loss from knee extension during the late phase of the 2000m race (Pollock et al., 2012). In muscle synergies studies, it has been shown that muscle coordination adapts to fatigue (So et al., 2007; Turpin et al., 2011; Shaharudin et al., 2014), but the kinematic coordination changes following fatiguing rowing are not yet clarified.

During the first and second 500m splits of 2000m timetrial, kinematics of hip joints in all planes and kinematics of both knee and ankle joints in the sagittal and frontal planes were contributors for Coordination #1 (i.e., the main coordination). It was shown that motions in the sagittal and frontal planes in all lower limb joints were crucial during the transition of drive and recovery phases. On the other hand, Coordination #2 comprised of the knee and ankle joints in the transverse plane and it was active during the middle of the drive and recovery phases. There was no redundancy of the factor loadings in the Coordination #1 and Coordination #2.

Meanwhile, during the third 500m split of the 2000m timetrial, there were changes of loading factors in Coordination #1 which included the kinematics of hip and knee joints in all planes and kinematics of ankle joint in the sagittal plane only. Coordination #1 was active during the transition of the drive and recovery phases. This situation might occur because the participants were ready to increase their stroke rates prior to the last 500m split. Moreover, Coordination #2 was contributed by the kinematics of knee joint in transverse plane and ankle joint in the frontal and transverse planes. On the other hand, there was a redundancy of the loading vectors in Coordination #2 despite varimax rotation that constrained the analysis to uncorrelated factors. The redundancy comprised of knee joint kinematics in the transverse plane that were activated in both Coordination #1 and #2, which might be attributed to the activity of two-joint knee adductor muscles surrounding the knee and hip joints.

During the last 500m split of the 2000m timetrial, there were changes of factor loadings in Coordination #1. The kinematics of hip joint in all planes and both knee and ankle joints in the sagittal and frontal planes contributed to Coordination #1 which occurred during the middle of the drive and recovery phases. Meanwhile, Coordination #2 consisted of the kinematics of knee joint in transverse plane and ankle joint in the frontal and transverse planes which were active during the end of the drive phase and the start of the recovery phase. There was a redundancy of kinematics of ankle joint in the frontal plane which was activated in both Coordination #1 and #2.

Humans select their movement coordination patterns via a process of self-organization within the context of organismic, environmental, and task-related constraints imposed on the degrees of freedom of its body system (Hancock & Newell, 1985). Besides, movement coordination is the process of mastering redundant biomechanical degrees of freedom of a moving body (Bernstein, 1967). Wilson et al., (2008) have thus suggested that a reduction in coordination variability will aid in the development of a skilled performance, which means that skilled player has consistent coordination. Hence, quantifying coordination needed in a specific skill may assist the skill development during training drill (Irwin &Kerwin, 2007). However, coordination variability present in the system also provides a degree of flexibility so that the system can search for the optimal solution. In simple words, coordination is robust and yet to be able of adapting to changes. Thus, an essential element in understanding movement dynamics is the degree of variability in the coordination patterns (Hamill et al., 1999). Furthermore, variability in movement is particularly important in many sports skills in which the adaptability of complex motor patterns is necessary within dynamic performance environments (Davids et al., 2006). In rowing, perfect synchronization of rower's movements is obligatory for the optimal performance of the crew as a whole (Baudouin& Hawkins, 2004). Thus, poor crew coordination may affect lower limb coordination, causing the rowing performance to be degraded and for the injury risk to increase (Thornton et al., 2016).

It has been noted previously that dynamic ergometer designs underestimate the kinetic energy required to accelerate the rower's center of mass during on-water rowing as the stroke rate and exercise intensity increase (Fleming et al., 2014). Moreover, muscles activities were markedly greater during on-water compared to dynamic ergometer rowing particularly in early drive and recovery phases (Fleming et al., 2014). This is because rowing ergometers are more stable than on-water rowing hence, additional activation of stabilizing 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. Dawson et al., (1998) analyzed the sources of variance and invariance for these two conditions in ergometer and on-water performance showing that in both conditions the major source of variability was the recovery phase. Moreover, they noted that the variability was less when rowing on ergometer than on water because laboratory-based study/research is controlled. On the contrary, on-water rowing has other confounding factors that can affect rowing and increased the variability such as weather, wind and water conditions (Kolumbet et al., 2018). Similarly, Kleshnev et al., (2005) found a higher value of handle force in the dynamic and stationary ergometers with respect to on-water rowing (30-40%) as well as a shorter stroke length in both ergometers. Differences have also been found in the handle velocity and shell acceleration profiles. Hence, the kinematics coordination determined in the current study may be limited to lower limb motions on dynamic ergometer.

Conclusions

To the best of our knowledge, this was the first study that evaluated joint coordination during 500m splits of 2000m rowing time trial among trained rowers. Joint coordination of lower limb kinematics can be distinguished in two robust factors which were consistent across 500m splits of 2000m of rowing time trial. Main coordination was contributed by hip joint in all planes, knee joint in sagittal and frontal planes as well as ankle joint in sagittal and transverse planes. Meanwhile, minor coordination was comprised of knee joint in transverse plane and ankle joint for the frontal plane. There were small changes in the loading vectors for both factors across the time trial. From our findings, coaches and rowers may emphasize their training on the specific joint movement contributing to the main coordination. This strategy may enhance their rowing performance and joint coordination.

Conflicts of interest

The authors have no conflicts of interest.

Acknowledgement

The study was funded by MOHE Fundamental Research Grant Scheme (203/PPSP/6171165), and UniversitiSainsMalaysia Bridging-Incentive Grant (304/PPSK/6316464). We thank RosniwatiGhafar for her assistance in one part of data processing, which was her only contribution as a member of the FRGS grant.

References

Baudouin, A., & Hawkins, D. (2004).Investigation of biomechanical factors affecting rowing performance.*Journal of Biomechanics,* **37**(7),pp. 969–976.

Bernstein, N. (1967). *The co-ordination and regulation of movements*. New York: Pergamon Press.

Caldwell, J.S., McNair, P.J., & Williams, M. (2003). The effects of repetitive motion on lumbar flexion and erector spinae muscle activity in rowers. *Clinical Biomechanics,* **18**, pp. 704–711.

Cattell, R.B. (1966). The scree plot test for the number of factors.*Multivariate Behavioral Research,* **1**(2),pp. 245–276.

Chen, H., Liu, C., & Yang, W. (2016).Coordination pattern of baseball pitching among young pitchers of various ages and velocity levels. *Journal of Sports Science,***34**(17),pp.1682–1690.

Comrey, A.L., & Lee, H.B. (1992).*Interpretation and application of factor analytic results.In A first course in factor analysis*. New York: Lawrence Earlbaum Associates; pp.442–450.

Cuijpers, L.S., Zaal, F.T., & de Poel, H.J. (2015).Rowing crew coordination dynamics at increasing stroke rates.*PloS one*, **10**(7),pp.0133527.

Davids, K., Button, C., Araújo, D., Renshaw, I., &Hristovski, R. (2006). Movement models from sports provide representative task constraints for studying adaptive behavior in human movement systems. *Adaptive Behavior,* **14**(1), pp.73–95.

Dawson, R.G., Lockwood, R.J., Wilson, J.D., & Freeman, G. (1998). The rowing cycle: sources of variance and invariance in ergometer and on-the-water performance. *Journal of Motor Behaviour,* **30**(1), pp.33–43.

Fleming, N., Donne, B., &Mahony, N. (2014). A comparison of electromyography and stroke kinematics during ergometer and on-water rowing.*Journal of Sports Science,* **32**(12), pp.1127–1138.

Greene, A.J., Sinclair, P.J., Dickson, M.H., Colloud, F., & Smith, R.M. (2009). Relative shank to thigh length is associated with different mechanisms of power production during elite male ergometer rowing. *Sports Biomechanics,* **8**(4), pp.302–317.

Hamill, J., van Emmerick, R.E., Heiderscheit, B., & Li, L. (1999).A dynamical systems approach to lower extremity running injuries.*Clinical Biomechanics (Bristol, Avon),* **14**(5), pp.297–308.

Hancock, P.A., & Newell, K.M. (1985).*The movement speed-accuracy relationship in space-time.* In: Heuer H., Kleinbeck U., Schmidt KH. (eds) Motor Behavior.Springer, Berlin, Heidelberg.

Heiderscheit, B., Hamill, J., &Emmerik, R.V. (2002).Variability of stride characteristics and joint coordination among individuals.*Journal of Applied Biomechanics,***18**,pp.110–121.

Hill, H. (2002). Dynamics of coordination within elite rowing crews: evidence from force pattern analysis. *Journal of Sports Science,* **20**(2), pp.101–117.

Holt, P.J., Bull, A.M., Cashman, P.M., & McGregor, A.H. (2003).Kinematics of spinal motion during prolonged rowing.*International Journal of Sports Medicine,* **24**,pp.597–602.

Hug, F., Turpin, N.A., Couturier, A., & Dorel, S. (2011). Consistency of muscle synergies during pedaling across different mechanical constraints.*Journal of Neurophysiology,* **106**(1), pp.91–103.

Irwin, G., &Kerwin, D.G. (2007).Inter-segmental coordination in progressions for the longswing on high bar.*Sports Biomechanics,* **6**, pp.131–144.

Ivanenko, Y.P., Poppele, R.E., &Lacquaniti, F. (2004). Five basic muscle activation patterns account for muscle activity during human locomotion. *Journal of Physiology,* **556**(1), pp.267–282.

Kaiser, H. (1974). An index of factor simplicity.*Psychometrika,***39**,pp.31–36.

Kipp, K., & Harris, C. (2015).Patterns of barbell acceleration during the snatch in weightlifting competition. *Journal of Sports Science,* **33**(14), pp.1467–1471.

Kleshnev, V. (2005).Comparison of on-water rowing with its simulation on Concept2 and rowperfect machines. Proceedings of XXII International Symposium of Biomechanics in Sports, pp.130–133.

Kline, P. (1994). *An easy guide to factor analysis*. New York: Routledge.

Kolumbet, A.N., Babina, N.A., Babina, T.G., Dudorova, L.Y., &Natroshvili, S.G. (2018). Study of the rowing technique major components. *Journal of Physical Education and Sport,***18**(4), pp. 1886–1889.

Lamb, D.H. (1989). A kinematic comparison of ergometer and on-water rowing.*American Journal of Sports Medicine,* **17**(3),pp.367–373.

Majumdar, P., Arnab, D., & Mandal, M. (2017).Physical and strength variables as a predictor of 2000m rowing ergometer performance in elite rower.*Journal of Physical Education and Sport,***17**(4), pp. 2502–2507.

McGregor, A.H., Patankar, Z.S., & Bull, A.M. (2005). Spinal kinematics in elite oarswomen during a routine physiological "step test". *Medicine and Science in Sports and Exercise,* **37,** pp.1014–1020.

Penichet-Tomas, A., Pueo, B., & Jimenez-Olmedo J.M. (2016).Relationship between experience and training characteristics with performance in non-Olympic rowing modalities.*Journal of Physical Education and Sport,***16**(4), pp. 1273–1277.

Pollock, C.L., Jones, I.C., Jenkyn, T.R., Ivanova, T.D., & Garland, S.J. (2012). Changes in kinematics and trunk electromyography during a 2000 m race simullation in elite female rowers.*Journal of Medicine and Science in Sports*, **22**,pp.478–487.

Shaharudin, S., & Agrawal, S. (2016). Muscle synergies during incremental VO2max test of collegiate rowers and untrained subjects. *Journal of Sports,Medicine and Physical Fitness,* **56**(9),pp.980–989.

Shaharudin, S., & Agrawal, S. (2015). Muscle synergy of collegiate rowers during 6 min maximal rowing on fixed and slides ergometer. *Journal of Medical and Bioengineering,* **4**(4),pp.263–269.

Shaharudin, S., Zanotto, D., & Agrawal, S. (2014). Muscle synergy during Wingate anaerobic rowing test of collegiate rowers and untrained subjects. *International Journal of Sports Science,***4**(5), pp.165–172.

So, R.C.H., Tse, M.A., & Wong, S.C.W. (2007). Application of surface electromyography in assessing muscle recruitment patterns in a six-minute continuous rowing effort. *Journal of Strength and Conditioning Research*, **21**(3), pp.724–730.

Tabachnick, B.G., &Fidell, L.S. (2007). *Using multivariate statistics*. 5th ed. Boston: Allyn & Bacon/Pearson Education.

Thornton, J.S., Vinther, A., Wilson, F., Lebrun, C.M., Wilkinson, M., Di Ciacca, S.R., &Smoljanovic, T. (2016). Rowing injuries: an updated review.*Sports Medicine,* **47**(4), pp.641–661.

Turpin, N.A., Guével, A., Durand, S., & Hug, F. (2011). Fatigue-related adaptations in muscle coordination during a cyclic exercise in humans.*Journal of Experimental Biology,* **214**(19), pp.3305–3314.

Wilson, C., Simpson, S., & Hamill, J. (2009). Movement coordination patterns in triple jump training drills.*Journal of Sports Science,* **27**(3), pp.277–282.

Wilson, C., Simpson, S.E., van Emmerik, R.E.A., & Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics,* **7**(1), pp.2–9.