AN INERTIAL SENSORS-BASED METHOD FOR PHASES AND EVENTS IDENTIFICATION IN PARA-ROWING: TOWARDS AN ON-WATER PERFORMANCE ASSESSMENT

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The aim of this study is to propose and validate an inertial sensors-based methodology for the para-rowing stroke cycles segmentation. One non-disabled athlete performed two para-rowing set-ups, simulating PR1 (arms and shoulders-AS) and PR2 (trunk and arms-TA) conditions. Catch and finish events of each stroke cycle were identified on the signals measured by three sensors located on the right forearm (FA), upper arm (UA), and on the trunk (T). Accuracy was quantified by identifying the same events on the 3D trajectory of one right hand-located marker. UA and FA sensors data lead to a more accurate detection of stroke events with respect to the T sensor (average error: 28.8ms, 29.0ms, 56.9ms). The present results open promising scenarios on the application of inertial sensors in para-rowing for real-time performance-related feedback to athletes and coaches.

KEYWORDS: wearable sensors, stroke cycle, athlete with disability.

INTRODUCTION: Rowing is a physically demanding sport that requires a coordinated motion of both upper and lower body over consecutive stroke cycles. To guarantee an optimal forward progression of the boat, the rower performs each stroke cycle as similarly as possible, while keeping a high force production rate. The rowing technique consists of a proper sequencing of two phases, the drive and the recovery, respectively defined by two positions, the catch and the finish (Bosch et al., 2015). The temporal segmentation of the stroke cycle facilitates the biomechanical analysis of the rowing technique and, hence, the evaluation of the role that the different body segments play within each phase. It has been shown that the trunk segment plays an important role in guiding the rowing movement, displaying a large range of motion and accounting for 75-90% of the total lumbar spine flexion-extension movement (Caldwell et al., 2003). This functional role of the trunk is however limited in the Para-rowing discipline, where the straps used to fasten the athlete with lower limbs dysfunction limits the range of motion of the spine. Aside from lumbar flexion, range of motion changes have been observed in the elbow flexion and shoulder abduction, influencing the upper body movement execution (Cutler et al., 2016). Depending on the degree of disability, rowers with lower limbs impairment are classified into two categories: the PR2 class, which includes athletes who can use upper trunk and arms and are fastened by straps at the pelvis level (TA), and the PR1 class, in which the straps are positioned around the athlete's trunk (sternum level) and only arms and shoulders are used to generate and transfer forces to the oars (AS) (World-Rowing, 2020). In both categories, the athlete is fastened to a fixed seat through straps around the thighs. Besides possible applications in the injury prevention field through the analysis of joint angles during the rowing movement, the temporal segmentation of the stroke cycle into the drive and recovery phases can provide useful information about the athletic performance. In particular, parameters such as stroke rate, drive and recovery duration, and drive to recovery time ratio are known to affect the rowing performance (Bingul et al., 2014; Sopher and Hume, 2004). In both papers, the identification of catch and finish events were automatically performed through an indoor rowing machine software, which however limits the applicability of the methodology to an outdoor context. New ecological approaches are therefore required in order to move the performance evaluation to the sport environment, removing the constraints of laboratory-based measurements. Magneto-Inertial Measurement Units (MIMUs) represent a suitable solution to this end, since portable and non-invasive. Indeed, they have been widely used in many different sport fields to monitor both able-bodied athletes (Camomilla et al., 2018) and athletes with disability (Rum et al., 2021). However, no study validated their use in the para-rowing field, where changes in the range of motion of trunk, shoulders and elbows due to the fixed seating position could undermine the accuracy of the existing protocols, mainly relying on MIMUs positioned on the equipment or on the athlete's trunk (Worsey et al., 2019). Therefore, the aim of the study was to propose and validate a methodology for the segmentation of the stroke cycle through portable MIMUs worn by an athlete with disability. This preliminary study wants to lay the foundations for a potential in-field application able to monitor and provide real-time feedback on the athletes' performance.

METHODS: One non-disabled experienced rower (38 years, female) was asked to perform two para-rowing set-ups. An indoor rowing machine (RowErg model E, Concept2, US) was equipped with a fixed seat (WinTech rowing para-7800L) clamped to the machine's rail, while a set of belts was used to simulate TA and AS conditions. Specifically, two belts were fastened around the thighs and pelvis to allow the motion of both trunk and arms while simulating the TA condition, whereas an additional belt was fastened at the thoracic level to limit trunk motion and reproduce the AS condition. The experimental setup included three MIMUs (Mtw Awinda, Xsens, Netherlands, sampling rate 100 frames/s) synchronized with an optoelectronic system (Vero, Vicon, UK, sampling rate 200 frames/s). The MIMUs were positioned on the dominant side (right) forearm (FA), upper arm (UA), and on the trunk (T) at T9 level, while one marker was attached on the dominant hand to track its motion during the drive and recovery phases of the rowing cycle. Each MIMU unit was visually aligned with the corresponding anatomical axes (x-axis, antero-posterior; y-axis: medio-lateral; z-axis, cranio-caudal). After a brief warm-up, the athlete was asked to perform a three-minute trial at a constant stroke rate (36 spm), for both TA and AS conditions. The stroke rate was displayed during each trial on the rowing machine monitor. The two trials were separated by five minutes of rest. For each trial, the time events corresponding to the catch and finish positions of 50 at regime strokes were identified from the right-hand marker trajectory and considered as reference, as in (Umar et al., 2018).

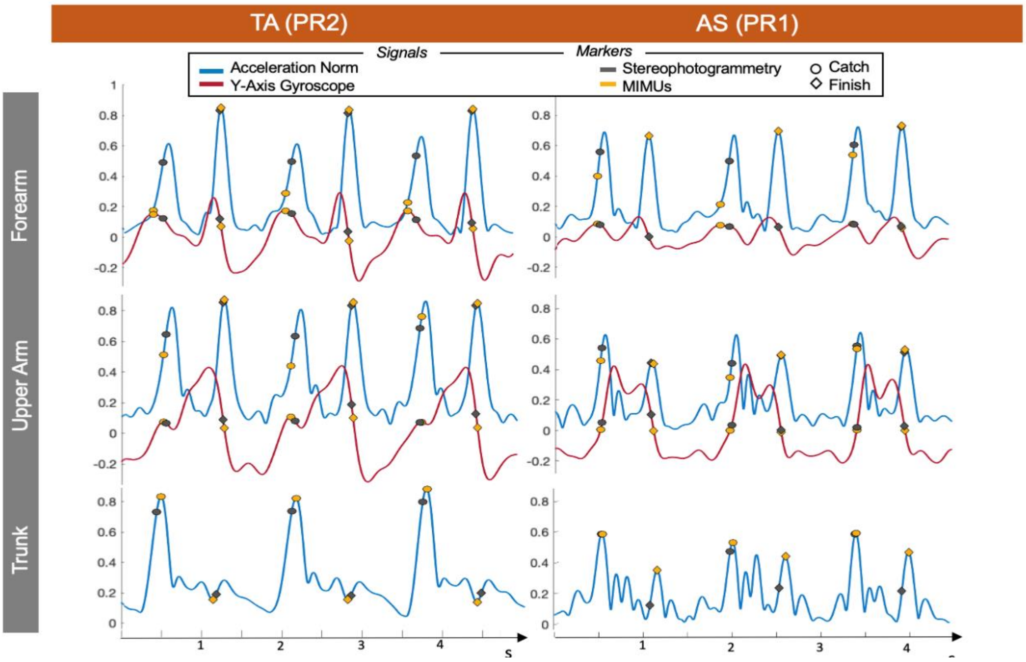
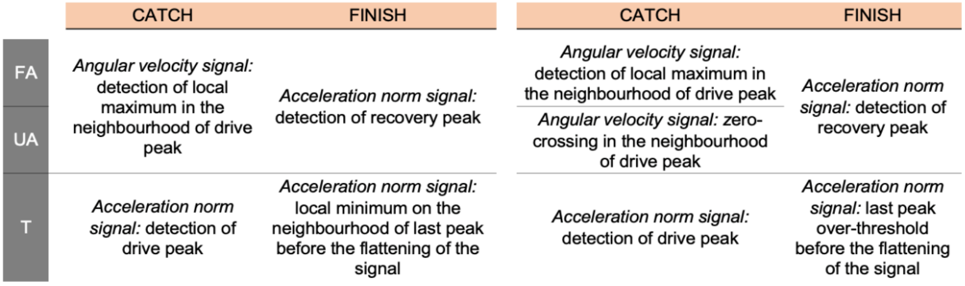


Figure 1: Normalized accelerations and angular velocities of FA, UA, T for three stroke cycles for both TA and AS conditions. Each signal was normalized to its maximum value.

Table 1: Gesture segmentation criteria

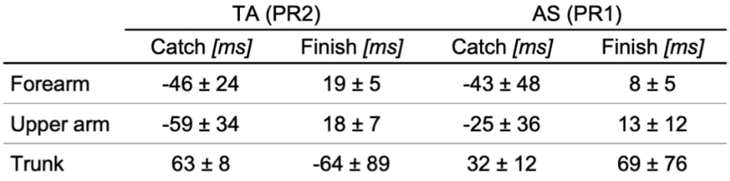


	CATCH	FINISH	CATCH	FINISH
FA	*Angular velocity signal:* detection of local maximum in the neighbourhood of drive peak	*Acceleration norm signal:* detection of recovery peak	*Angular velocity signal:* detection of local maximum in the neighbourhood of drive peak	*Acceleration norm signal:* detection of recovery peak
UA			*Angular velocity signal:* zero-crossing in the neighbourhood of drive peak	
T	*Acceleration norm signal:* detection of drive peak	*Acceleration norm signal:* local minimum on the neighbourhood of last peak before the flattening of the signal	*Acceleration norm signal:* detection of drive peak	*Acceleration norm signal:* last peak over-threshold before the flattening of the signal

MIMUs signals were filtered with a 4th order Butterworth lowpass filter, with a cut-off frequency of 4 Hz (Worsey et al., 2019). Six segmentation algorithms were implemented to detect the catch and finish positions from each MIMU sensor in both TA and AS conditions (3 MIMUs x 2 conditions): signal waveforms are reported in Figure 1, segmentation criteria are reported in Table 1. The accuracy of each algorithm was obtained, for each detected event, as the difference between the time instant identified on the MIMU signal and the one identified on the marker trajectory along the main axis of the rowing movement. The detected instants were visually inspected to number the wrong identification of the stroke event. In addition, mean drive and recovery phase durations, as well as drive to recovery ratio, were computed from marker trajectory data in each condition.

RESULTS: The mean duration of the drive and recovery phases were respectively 0.74 s and 0.95 s for TA condition, and 0.62 s and 0.98 s for AS condition. The drive to recovery ratio (TA: 0.78, AS: 0.63) for both the categories was definitely lower with respect to non-disabled rowers, whose ratio ranges from 0.9 to 1.8 (Torres-Moreno et al., 2000). The accuracy of each algorithm in the detection of the catch and finish events is reported in Table 2. While the segmentation algorithms based on FA and UA signals were able to detect both events across all strokes (0% of missing or extra events), the T-based algorithm resulted in 4% of missing and 2% of extra events. Due to the similarities of the signal waveforms and to the consistent segmentation criteria (Figure 1), the FA and UA-based algorithms exhibited similar results: the detection of the finish event was the most accurate, reporting a systematic delay of about 15 ms, while the catch event was early detected (about 46 and 60 ms, respectively). On the contrary, the T-based algorithm showed a more accurate detection of the catch position, with the detection of the finish position being characterized by a greater variability.

Table 2: Time errors (mean +/- standard deviation across 50 stroke cycles) related to the catch and finish events detection are reported in the table.



	TA (PR2)		AS (PR1)	
	Catch *[ms]*	Finish *[ms]*	Catch *[ms]*	Finish *[ms]*
Forearm	-46 ± 24	19 ± 5	-43 ± 48	8 ± 5
Upper arm	-59 ± 34	18 ± 7	-25 ± 36	13 ± 12
Trunk	63 ± 8	-64 ± 89	32 ± 12	69 ± 76

DISCUSSION: In the present study, acceleration and angular velocity signals measured by FA, UA and T-MIMU were exploited to develop and validate different segmentation algorithms during para-rowing stroke cycles against reference hand-located marker trajectory. The accuracy of the proposed algorithms ranged from 8 ms to 69 ms, which can be considered as acceptable for most para-rowing contexts. Information coming from both FA and UA sensors led to a more accurate detection of stroke events with respect to the T-sensor. In fact, both accelerations and angular velocities (along and about the medio-lateral axis) of the FA and UA MIMUs signals displayed a regular and repeatable behaviour, with easily detectable features.

On the contrary, irregular T accelerations and angular velocities proved to be less suitable for detecting the catch and finish events, despite the drive peak was distinguishable in both TA and AS conditions. In para-rowing, the functional role of the trunk in guiding the stroke movement is limited due to the equipment set-up (i.e., thigh, pelvis and thoracic straps). As a consequence, upper limbs may play a more dominant role in the rowing action. In line with this, the results of this preliminary study seem to indicate a greater reliability of arm sensors in detecting the events of the rowing cycle, thereby making them a more suitable location for movement temporal segmentation. Despite an overall similarity of the FA and UA MIMU-signals between the two conditions, some peculiar differences due to movement execution were found. Specifically, the limitation of the trunk excursion provided by the AS setup requires a greater amount of elbow flexion (Cutler 2017), which resulted in a sharper pattern of the angular velocities signals of both FA and UA in correspondence of the catch. As a result, the time error in AS was approximately halved with respect to the TA condition, when selecting the upper arm MIMU for the detection of the catch. Furthermore, both UA and FA positioning had similar error values for catch and finish instant definition in the TA condition, whereas time error of catch identification was grater for FA compared to UA positioning (approximately 20 ms). Overall, these results suggest that the para-rowing condition should be taken into account when selecting the sensor placement for temporal segmentation of the stroke movement. In particular, the MIMU positioned on the UA may be the most promising solution for the AS category, while both the FA and UA are suitable for the identification of the catch and finish events in TA.

CONCLUSION: The present results confirm the potential role of MIMUs in adaptive sport applications (Rum et al., 2021). Sensor placement on the FA and UA appeared to be the most adequate for the detection of rowing phases and events in different para-rowing set-ups. The correct temporal segmentation of the rowing action enables the identification of parameters related to the drive and recovery phases. These parameters could be adopted in ecological on-water conditions to provide real-time feedback to the para-rowing athletes and coach about movement execution, possibly reducing the risk of injury related to wrong technical gestures.

REFERENCES

Bingul, B. M., Aydin, M., Buyukdemirtas, T., Ozbek, A., & Bulgan, C. (2014). Two-dimensional kinematic analysis of catch and finish positions during a 2000m rowing ergometer time trial. South African Journal for Research in Sport, Physical Education and Recreation, 36(3), 1-10.

Bosch, S., Shoaib, M., Geerlings, S., Buit, L., Meratnia, N., & Havinga, P. (2015). Analysis of indoor rowing motion using wearable inertial sensors. Proceedings 10th EAI International Conference on Body Area Networks (pp. 233-239).

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(8), 704-711.

Camomilla, V., Bergamini, E., Fantozzi, S., & Vannozzi, G. (2018). Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: A systematic review. Sensors, 18(3), 873.

Cutler, B., Eger, T., Merritt, T., & Godwin, A. (2017). Comparing para-rowing set-ups on an ergometer using kinematic movement patterns of able-bodied rowers. Journal of sports sciences, 35(8), 777-783.

Para-Rowing Classification. (n.d.). World Rowing. Retrieved April 16, 2021, from https://worldrowing.com/technical/para-rowing-classification/

Rum, L., Sten, O., Vendrame, E., Belluscio, V., Camomilla, V., Vannozzi, G & Bergamini, E. (2021). Wearable sensors in sports for persons with disability: a systematic review. Sensors, 21(5), 1858.

Soper, C., & Hume, P. A. (2004). Towards an ideal rowing technique for performance. Sports Medicine, 34(12), 825-848.

Torres-Moreno, R., Tanaka, C., & Penney, K. L. (2000). Joint excursion, handle velocity, and applied force: a biomechanical analysis of ergonometric rowing. International journal of sports medicine, 21(01), 41-44.

Umar, M. A., Zainuddin, F. L., Razman, R. M., Shaharudin, S., & Kesihatan, P. P. S. (2019). Changes of drive to recovery ratio during 2000m ergometer rowing among junior national rowers. Malaysian Journal of Movement, Health & Exercise, 8(1), 33-43.

Worsey, M. T., Espinosa, H. G., Shepherd, J. B., & Thiel, D. V. (2019). A systematic review of performance analysis in rowing using inertial sensors. Electronics, 8(11), 1304.