Validity of smartphones for assessing kayak paddler training

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Running Title: Kayak training assessment with smartphones

Abstract

Over the last few years, the use of automatic performance measurement systems has become relatively common among professional kayak paddlers. Although these systems are not able to perform a complete evaluation of the athlete, they can extract relevant parameters about the training result. Thus, different devices have been developed to measure relevant information such as paddling rhythm. The high price of these devices limits their use for amateur athletes. To overcome this limitation, the validity of the measurements provided by different smartphones, obtained from the integrated inertial sensors, has been analyzed. This study has compared the performance of different phones versus professional Movella DOT inertial measurement devices. The article presents a comparison of the results obtained and proves that smartphones produce results equivalent to those of conventional sensors.

Keywords: kayaking, inertial measurement, IMU, accelerometers, smartphone measurement, national Spanish women's junior kayak team, paddling rate, automatic performance measurement systems, Movella, Xsens

Introduction

Kayaking is a sport that has seen extensive research on performance and physiology, but very little on technical aspects. Technical research in this field has primarily focused on vessel design [1], with only recent efforts being made to explore the use of technological tools for monitoring athlete training and to assist coaches [2]. Robinson et al. [3] showed that an accelerometer placed in the kayak could be used to evaluate the paddling rate and left/right stroke rate asymmetries. It was also possible to identify acceleration patterns. Subsequent to

Robinson's work, inertial measurement systems have become popular among professional coaches [4].

Several studies have verified the reliability of the use of accelerometers. Janssen et al. [5] verified that the mean value of the accelerometer-estimated stroke rate and the velocity estimation were similar to those provided by video measurements. McDonnell et al. [6] studied the reliability of the calculation of the stroke rate by accelerometry. Combined with the work shown in McDonnell et al. [7], which shows that stroke rate is the main determinant of performance, [6] demonstrates the validity of using accelerometry for training. Other possible avenues for the use of accelerometry are drawn by Brown et al. [8] whose research relates the percentage of time in the air and water phase and the level of technicality of the athlete. Recent studies [9][10], show that the combination of inertial sensors and GPS can be used to evaluate the distance of stroke and the fatigue index. Liu et al. [11] also showed that inertial sensors can be used for the evaluation of human posture during racing.

Most of the studies have been conducted using custom-developed technology designed for use in kayaks, such as the e-kayak system [12]. These systems allow for the measurement of multiple training parameters but are expensive and challenging for amateur athletes to use. Shaw et al. [9], however, showed that amateur athletes have a strong preference for the use of smartphones to evaluate their performance. Smartphones have been evaluated for other athletic applications, such as gait assessment [13] or the assessment of joint movement ranges [14].

This study aims to demonstrate the validity of using a smartphone for the monitoring of kayak training. To this end, a series of tests have been developed to compare the acceleration measurements, the estimated stroke rate and the kayak oscillations between a Movella DOT inertial sensor [v2, Movella Inc., USA] and a selection of smartphones.

Methods

The experiments were carried out with the support of the National Spanish Women's Junior Kayak Team. In that experiment, five female team members participated, all of them aged between 17 and 18 years old. All participants, as well as their coach, provided written consent in advance for the study to be conducted. The experiments were carried out in the Trasona Reservoir in Asturias, Spain, during a regular training session for the team. No personal data were recorded for any of the participants. Each of the kayaks carried out three training tests. First, a 500m test was performed, with a gradual increase in pace, from pace one to pace five. The second test was also a 500m test, starting at maximum pace and gradually decreasing the pace. Finally, a group race was carried out with a total distance of approximately 2km.

For the experiment a Movella DOT sensor was installed in each kayak. The sensor was located on the outside of the kayak, behind the kayaker. In each of the boats, a different smartphone was used, positioned directly underneath the Movella DOT sensor. The sensor and smartphone set was installed inside a watertight container. A camera was placed at the back of the kayak to monitor the training, and to allow manual counting of the paddle strokes. The cameras were positioned so that the athlete could not be identified.

Low-end and old android cell phones were chosen for the test, as it was considered that in normal practice athletes would be reluctant to use an expensive or new cell phone in a kayak. The list of phones used is shown in Table 1, including their main features, alongside the specifications of the Movella DOT sensors. The hardware features of the sensors are similar in all cases, although the Movella DOT sensor has the advantage of being individually calibrated by its manufacturer and is the only one of the devices that specifies the standard deviation when estimating spatial orientation.

The inertial sensors were manually aligned with the longitudinal, transverse, and vertical axes of the kayak. The sampling frequencies were 60Hz for the inertial sensors and 240Hz for the smartphone. This high frequency was chosen because the smartphone cannot sample at a truly periodic frequency. The signals from both sensors were synchronized by registering a sharp acceleration in both sensors at the beginning and end of the sample by means of a sharp tap over the box containing the devices. To apply the same algorithms to both sensors, the frequency of the smartphone was downsampled from 240Hz to 60Hz. A zero phase FIR anti-aliasing filtering at a frequency of 30Hz was applied prior to the decimation. Figure 1(a) shows the forward accelerations recorded by the two devices after the decimation process. The camera was used to determine the beginning and end of each stint, and to perform a manual count of the number of strokes. The manual counts were completed by two researchers independently.

Each of the strokes is associated with a cycle in forward acceleration. For the detection and counting of the strokes a windowed-sync, low pass, zero phase, order 60 filter has been implemented, with a Hamming window and a filtering frequency of 5Hz. An algorithm that detects the maxima and minima of the filtered signal has been implemented. Occasionally the signal showed additional oscillations to the paddling rhythm, which could be due to loss of balance in the kayak, balance strokes or other artifacts. To remove these potentially erroneous data, the maximums that are not positive or that have a value lower than the mean value of the last 100 measurements are discarded. The same process is applied to the minima of the acceleration signal.

For the estimation of pitch, roll and yaw angles we have taken the quaternion corresponding to the orientation of the Movella DOT sensor and the estimated by the android system and compared them with each other. The comparison was carried out on each of the axes independently.

Results

Figure 1 depicts a comparative graph of forward accelerations recorded by the Movella DOT and the smartphone during the first strokes for one of the kayaks. No notable differences are observed in the temporal or frequency representation of both signals.

Table 2 shows the results of the estimation of the number of strokes by both methods compared to the actual value. The estimated values differ from the actual value by at most one or two strokes. These variations always correspond to the first or last stroke of the series. The second test of kayak number five is the only exception (both methods over-counted four strokes).

From the detection of the strokes, it is possible to determine the instantaneous frequency of the stroke. Both estimations are similar, although the frequency estimated by the smartphone oscillates more within each section, as shown in Figure 2.

Finally, the roll, pitch and yaw angles estimated by both methods have been compared by means of a Bland-Altman plot, as shown in Figure 3. For roll estimation, a high correlation has been obtained, with a value of the r^2 factor equal to 0.96, an average difference of only 0.15 degrees and limits of agreement of +1.2 degrees and -1.5 degrees. In the case of pitch the correlation coefficient is much lower, being the r^2 factor of only 0.05, mean error of 0.04 degrees and limits of agreement of 0.77 and -0.84 degrees. Finally, for yaw angles the correlation is also low, with an r^2 factor of 0.07 and limits of agreement of 5.1 and -5.4 degrees.

Discussion

In this work we have analyzed the possibility of using smartphones for monitoring kayak paddling. We have used a variety of cheap smartphones, and it is foreseeable that higher-end and/or more modern phones may improve these results. In practice, athletes will find it difficult to determine the exact technical characteristics of their smartphones, because manufacturers do not provide information about the accelerometers and gyroscopes built into the phones. For this reason, we have chosen to analyze the different devices as a group.

The results of the stroke count are excellent, with almost no deviation. No significant difference was observed between the results of the smartphones and the Movella DOT sensor. All deviations from the manual stroke count were observed in instances where the strokes made a minimal or almost negligible contribution to propelling the boat forward (to maintain balance or to control the trajectory when letting go). This result extends to the estimation of the stroke frequency. Both methods give a similar estimate, although estimates obtained by the smartphone oscillate more than those of the Movella DOT, probably due to the irregular sampling period.

In the evaluation of the kayak rotation angles, non-uniform results have been obtained. In the case of roll angles, the estimation has been very good, while the results are poor for pitch and yaw angles. This difference may be because the roll angles are larger so that an error of the same magnitude means a much smaller percentage variation. Furthermore, it is clear that the measurement noise effectively conceals pitch and yaw angles.

For this study, data was captured and subsequently subjected to offline analysis. Nevertheless, all the algorithms used can be employed in real-time with minimal adaptation. The only filter that wouldn't work in real-time is the zero phase FIR filter (order 60) used for stroke detection. A non-zero phase FIR filter can replace this filter, with the only consequence being the introduction of a delay of 29.5 samples in the signal. With a sampling frequency of 60Hz, the delay doesn't exceed half a second, which would have little effect on its visualization by the athlete or coach.

Conclusion

Experiments have shown that smartphones are a valid alternative to professional inertial measurement devices for counting the number of strokes and estimating paddling pace during kayaking. Smartphones have also been able to estimate the roll angles of the boat, but not the pitch and yaw angles. The study was conducted exclusively in still water; variations may arise in other conditions such as more turbulent waters or real racing situations where the technical gestures of the paddler may occasionally deviate from the normal paddling pattern. The results of stroke count and frequency estimation are expected to be more robust than those corresponding to the boat's rotation angles.

The fundamental impact of incorporating this technology into smartphones is that it would make it accessible to the general public, which lacks access to specialized measuring devices or high-end smartwatches. Compared to smartwatches, smartphones enhance visualization capabilities, as the results could be displayed graphically and viewed in real-time with negligible delay.

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References

1. Robinson MG, Holt LE, and Pelham TW. The technology of sprint racing canoe and kayak hull and paddle designs. *International Sports Journal*. 2002; 6(2), 68-85.
2. Li M. The progress of Biomechanical Researches in Kayaking. *Yangtze Medicine*. 2017;1(1) 30-44. doi:10.4236/ym.2017.11004
3. Robinson MG, Holt LE, Pelhan TW. et al. Accelerometry measurements of sprint kayaks: the coaches' new tool. *International Journal of Coaching Science*. 2011;5(1), 45-56.
4. Vadai G, Makan G, Gingl Z et al. On-water measurement and analysis system for estimating kayak paddlers' performance. *36th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, 2013;131-136, Opatija, Croatia.
5. Janssen I, and Sachilikidis A. Validity and reliability of intra-stroke kayak velocity and acceleration using a GPS-based accelerometer. *Sports Biomech.* 2010;9(1), 47-56. doi:10.1080/14763141003690229
6. McDonnell L, Hume P, and Nolte V. Sprint kayaking stroke rate reliability, variability and validity of the Digitrainer accelerometer compared to Gopro video measurement. *30th International Conference of Biomechanics in Sport*. 2012. 316-319. Melbourne. Australia.
7. McDonnell L, Hume P, and Nolte V. A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. *Sports Biomech.* 2013;12(3), 205-20. doi: 10.1080/14763141.2012.760106
8. Brown BM, Lauder M and Dyson R. Notational analysis of sprint kayaking: Differentiating between ability levels. *International Journal of Performance Analysis in Sport.* 2011;11(1), 171-183. doi:10.1080/24748668.2011.11868538
9. Shaw MP, Satchell LP, Thompson S et al. Smartphone and tablet software apps to collect data in sport and exercise settings: Cross-sectional international survey. *JMIR Mhealth Uhealth*. 2021;9(5). doi:10.2196/21763
10. Pickett CW, Abbiss C, Zois J et al. Pacing and stroke kinematics in 200-m kayak racing. *Journal of Sports Sciences*. 2020;39(10), 1096-1104. doi:10.1080/02640414.2020.1859242
11. Liu L, Wang H, Qiu S et al. Paddle stroke analysis for kayakers using wearable technologies. *Sensors*. 2021;21(3), 914. doi:10.3390/s21030914
12. Bonaiuto V, Gatta G, Romagnoli C et al. A pilot study on the e-Kayak system: A wireless DAQ suited for performance analysis in flatwater sprint kayaks. *Sensors.* 2020,20(2);542.doi:10.3390/s20020542
13. Howell DR, Lugade V, Taksir M et al. Determining the utility of a smartphone-based gait evaluation for possible use in concussion management. *Phys Sportsmed.* 2020;48(1), 75-80. doi:/10.1080/00913847.2019.1632155
14. Aparecido Dos Santos R, Derhon V, Brandalize M et al. Evaluation of knee range of motion: Correlation between measurements using a universal goniometer and a smartphone

goniometric application. *J Bodyw Mov Ther*. 2017;21(3), 699-703. doi:10.1016/j.jbmt.2016.11.008

Tables

Table 1: Specifications of the smartphones and the Movella DOT sensor. All sensors have a range of 16g and 2000°/s. The Movella DOT sensor is the only one individually calibrated by the manufacturer and guarantees an orientation accuracy of one degree for inclinations and two degrees for heading.

	Phone 1	Phone 2	Phone 3	Phone 4 & 5	IMU
Manufacturer	Xiaomi	Xiaomi	Xiaomi	Xiaomi	Movella
Model	Redmi 4	Redmi Note 4	Mi A1	Mi A2 Lite	Movella DOT
Android Version	6.0.1	7	9	10	N/A
SOC	Snapdragon 625	Snapdragon 625	Snapdragon 625	Snapdragon 625	N/A
RAM	3GB	4GB	4GB	4GB	N/A
Accelerometer & Gyroscope	Bosch BMI160	Bosch BMI160	Bosch BMI120	STMicroelectronics LSM6DS3	N/D
Magnetometer	Yamaha YAS537	Yamaha YAS537	AKM AK09918	AKM AK09918	N/D
Sample Rate	240Hz	240Hz	240Hz	240Hz	120Hz
Sensitivity	2048 LSB/g 16.4 LSB/°/s	2048 LSB/g 16.4 LSB/°/s	2048 LSB/g 262 LSB/°/s	2048 LSB/g 14.3 LSB/°/s	2048 LSB/g 16.4 LSB/°/s
Noise Density	180 [µg/√Hz] 0.007[°/s/√Hz]	180 [µg/√Hz] 0.007[°/s/√Hz]	300 [µg/√Hz] 0.010[°/s/√Hz]	130 [µg/√Hz] 0.005[°/s/√Hz]	120 [µg/√Hz] 0.007[°/s/√Hz]
Weight	156g	175g	165g	178g	11.2g
Size	141x70x8.9mm	151x76x8.3 mm	155x76x7.3 mm	149x72x8.7 mm	36x30x10.8 mm
Orientation Performance	N/D	N/D	N/D	N/D	1.0°-2.0°

N/A: Not Applicable. N/D: Not disclosed.

Table 2: Comparison of the number of strokes registered in each kayak, in each stretch.

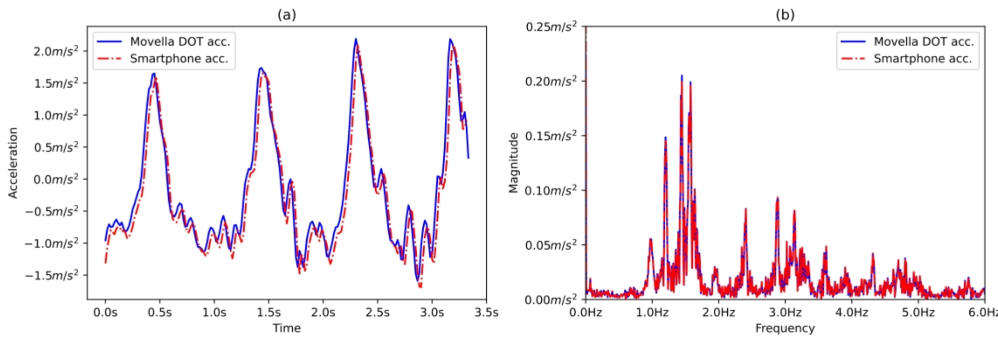
Kayak	Stretch 1 Actual	Stretch 1 Movella DOT	Stretch 1 Phone	Stretch 2 Actual	Stretch 2 Movella DOT	Stretch 2 Phone	Stretch 3 Actual	Stretch 3 Movella DOT	Stretch 3 Phone
1	177	176	176	169	169	169	702	702	702
2	194	195	195	175	175	175	712	713	713
3	186	186	187	209	211	211	722	721	720
4	212	212	212	186	186	186	750	750	751
5	202	201	201	214	218	218	770	770	770

Figure Captions

Figure 1: A Comparative graph of forward accelerations recorded by the Movella DOT and a smartphone during the first strokes for one of the kayaks is presented. The synchronization between the two devices is correct, although there is a small offset. (a) Depicts a temporal comparison, where both signals exhibit the same pattern of changes except for the slight offset. (b) Shows a frequency analysis of the signals, revealing that all the primary components of the motion are below 3Hz. The amplitude of both signals coincides throughout the relevant frequency spectrum.

Figure 2: A visual comparison of estimated stroke frequencies from five kayaks' sensors during a paddling course with five constant paddling rates, ranging from rate one to rate five (maximum effort). The solid line shows the frequency estimated by the Movella DOT sensor located in the kayak. The dashed line shows the frequency estimated from the cell phone. Both signals are very similar, although the frequency estimated by the cell phone seems to oscillate slightly more within each section.

Figure 3: The figure shows the Bland-Altman plots for comparison of the rotation estimates made by the Movella DOT (labeled as IMU in the figure) and those made by the smartphone (labeled as phone). Row (a), yaw (b) and pitch (c) plots are shown.



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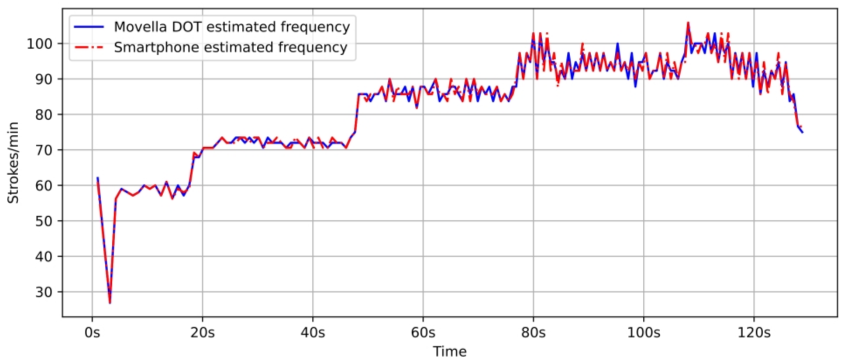
304x101mm (300 x 300 DPI)



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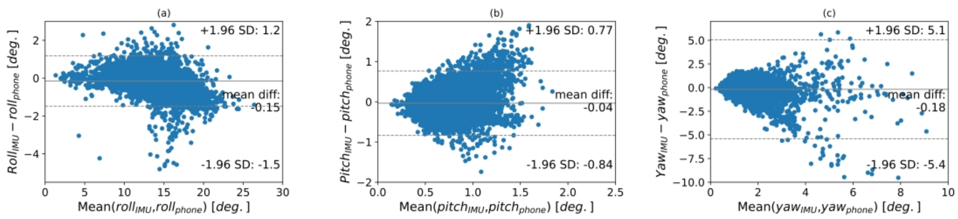

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