AÇIK ERİŞİM
OPEN-ACCESS

Gazi Beden Eğitimi ve Spor Bilimleri Dergisi
Gazi Journal of Physical Education and Sports Sciences
2023, 28(2), 142-149

A Simplified Method for Determining Swimming Arm-Stroke and Kick Durations Using Wearable Inertial Measurement Units

Yüzmede Kol Çekişi ve Ayak Vuruşu Sürelerini Belirlemede Giyilebilir Atalet Ölçüm Birimlerini Kullanarak Basitleştirilmiş Bir Yöntem

Research Article / Araştırma Makalesi

Ugur ÖDEK[1]
Kürşat ÖZCAN[1]

[1] Nevşehir Hacı Bektaş Veli University, Faculty of Sport Sciences, Nevşehir, TURKEY

Corresponding Author / Sorumlu Yazar
Ass. Prof. Dr. Üyesi Uğur ÖDEK
ugurodek@gmail.com

Received / Geliş Tarihi : 27.10.2022
Accepted / Kabul Tarihi : 18.03.2023
Published / Yayın Tarihi : 30.04.2023

Ethical Statement / Etik Bilgilendirme
This research was approved by the Nevşehir Hacı Bektaş Veli University Ethics Committee dated 28.03.2022 and numbered 2022.03-31-2100081420.

DOI: 10.53434/gbesbd.1195632

Abstract

The use of inertial measurement units (IMU) by the coaches has not reached the desired level, especially due to the complexity of the data processing. The aim of the study is to demonstrate that raw acceleration data obtained from IMUs can be used in swimming technical analysis by individuals operating in the field after processing with simple filtering methods. For this aim, the arm-stroke and kicking durations of the swimmers were determined using the acceleration data obtained from the IMUs and the agreement with the times obtained from the video recordings was examined. Five female (18.2±.84 years; 1.69±.04 m; 60.76±1.86kg) and 5 male (19.6±2.41 years; 1.81±.03 m; 81.2±2.69 kg) competitive swimmers participated to the study. Data was collected via two high-speed cameras and four IMUs which were placed bilaterally to the ankles and wrists of the swimmers. Bland-Altman method were used to examine the agreement. One-Sample T-tests were used to test whether the difference between the two measurements differed significantly from the "0". The majority (except 4) of the differences in arm-stroke and kicking cycle durations were within the limits of agreement. T-tests indicated that all the differences between the data obtained from two different measurement methods were not different from 0 (p>.05). Results showed that the accelerometer data alone, without fusion with other data or processed with complex algorithms can be used with ease for investigating temporal variables of swimming techniques.

Keywords: Swimming, Inertial measurement unit, Wearable technology, Arm-stroke, Kicking

Öz

Atalet ölçüm birimlerinin (IMU) antrenörler tarafından kullanımı özellikle veri işleme sürecinin karmaşıklığı nedeniyle istenilen düzeye ulaşamamıştır. Çalışmanın amacı IMU'lardan elde edilen ham ivmelenme verilerinin basit filtreleme yöntemleri ile işlenmesinin ardından alanda faaliyet gösteren bireyler tarafından yüzmede teknik analizlerde kullanılabileceğinin ortaya koyulmasıdır. Bu amaç doğrultusunda IMU'lardan elde edilen ivmelenme verilerinden yüzücülerin kol çekişi ve ayak vuruşu süreleri belirlenmiş ve video kayıtlarından elde edilen süreler ile uyumu incelenmiştir. Çalışmada 5 kadın (18.2±.84 yıl; 1.69±.04 m; 60.76±1.86 kg) ve 5 erkek (19.6±2.41 yıl; 1.81±.03 m; 81.2±2.69 kg) müsabık yüzücü katılımcı olarak yer almıştır. İvemelenme ve görüntü verileri, yüzücülerin ayak ve el bileklerine bilateral olarak yerleştirilen dört adet IMU ve iki adet yüksek hızlı kamera ile toplanmıştır. Uyumun incelenmesinde Bland-Altman yöntemi kullanılmıştır. İki ölçüm arasındaki farkın "0" dan önemli ölçüde farklı olup olmadığını test etmek için ise Tek Örneklem T-testi kullanılmıştır. Kol çekişi ve ayak vuruşu döngüsü sürelerindeki farklılıkların çoğu (4'ü hariç) uyum sınırları içinde yer almıştır. T-testleri iki farklı ölçüm yönteminden elde edilen veriler arasındaki tüm farklılıkların 0'dan farklı olmadığını göstermiştir (p>.05). Sonuçlar, ivmeölçer verilerinin tek başına, diğer verilerle birleştirilmeden veya karmaşık algoritmalarla işlenmeden yüzme tekniklerinin zamansal değişkenlerini incelemek için kolaylıkla kullanılabileceğini göstermiştir.

Anahtar Kelimeler: Yüzme, Atalet ölçüm birimi, Giyilebilir teknoloji, Kol çekişi, Ayak vuruşu

Citation / Atıf: Ödek, U. & Özcan, K. (2023). A simplified method for determining swimming arm-stroke and kick durations using wearable ınertial measurement units. *Gazi Journal of Physical Education and Sports Sciences, 28*(2), 142-149.

Giriş

Sport-related tasks are performed uniquely by each athlete and the way athletes exhibit these tasks is called technique (Lennox, Rayfield & Steffen, 2006). In cyclic sports such as cycling, running and swimming where a particular movement is repeated continuously, the athlete's technique is one of the main factors that determine overall performance (Engel, Schaffert, Ploigt, & Mattes, 2021; Marinho, Barbosa & Neiva, 2013). Due to the cyclical nature of motion, a technical error can result in a cumulative loss in performance. Swimmers devote some of their training programs to technical development in order to improve their performances (Bächlin & Tröster, 2012; Nugent, Comyns & Warrington, 2017). It is not always easy to perceive self-technical errors in sports such as swimming where each part of the body needs to work simultaneously, in coordination and without any visual feedback. Therefore, swimmers often need external (augmented) feedback. Although external feedback has a variety of sources, it is usually provided by coaches (Pérez, Llana, Brizuela, & Encarnación, 2009; Schaffert, Engel, Schlüter & Mattes, 2019). On the other hand, coaches often rely on their eyes while they are on deck and provide feedback to their athletes to correct visible errors. This method is useful and very practical during daily training sessions, however, it should be noted that many subtle errors may not be detected or overlooked (Callaway, 2015; Mooney et al., 2016; Wilson, 2008).

High-speed cameras have been used for technical analyses in swimming for many years and are still the most common data collection tool (Mooney et al., 2015). However, images obtained from camera recordings alone are insufficient to analyze the technique quantitatively. In order to quantify or digitize the motion and to calculate the kinematic variables, software specially written for this purpose is usually required (Callaway, Cobb & Jones, 2009). The video-based motion analysis method is accepted as the gold standard in examining the techniques of athletes and gives the chance of visual monitoring of performance during and after analysis as an advantage (Pansiot, Lo & Yang, 2010). Nevertheless, it has some disadvantages limiting the usage such as cost, limited field of view, long setup time, sensitivity (light, water, humidity etc.), and occlusion of the movement (Ceseracciu et al., 2011; Monnet, Samson, Bernard, David & Lacouture, 2014; Silvatti et al., 2013). In addition, the process of getting the data ready for analysis (post-processing) can be quite long, especially when the manual digitization method is used(Le Sage et al., 2010; O'Reilly, Caulfield, Ward, Johnston & Doherty, 2018)

Breakthroughs in wearable technology have occurred over the past two decades. With the development of electronics and design, the sensors have decreased in size, the data collection rate and accuracy have increased, and they have become able to transfer data wirelessly at high speed and become more ergonomic (Ahmad, Ghazilla, Khairi & Kasi, 2013). These sensors, which had only accelerometers in the first periods, were later added 3 axes gyroscope and a magnetometer and turned into a measurement unit called inertial measurement unit (IMU). IMUs have started to be used as an alternative to video-based motion analysis systems due to some advantages they offer, including low cost, durability and easy installation on the body (Engel, Ploigt, Mattes & Schaffert, 2021; Tolza, Soto-Romero, Fourniols & Acco, 2017). The advantages and disadvantages of using video-based and IMU technologies in swimming motion analysis are given in detail in the review article of Guignard, Rouard, Chollet, and Seifert (2017).

IMUs were used to estimate temporal and kinematic variables as well as to determine the stroke type, stroke rate and phases of stroke in swimming (Hamidi Rad, Gremeaux, Dadashi & Aminian, 2021; Magalhaes, Vannozzi, Gatta & Fantozzi, 2015; Stamm & Shlyonsky, 2020; Zhang et al., 2017). The results of studies aiming to identify temporal variables such as total swimming, lap, glide, turn times, stroke count and stroke rate usually are consistent with the studies using video-based motion analysis (Callaway et al., 2009; Davey, Anderson & James, 2008; Slawson, Justham, Conway, Le-Sage & West, 2012). In recent studies, researchers also use other sensor data of IMUs in order to increase the accuracy of the data. In these studies, it is seen that the data obtained from gyroscopes, accelerometers and magnetometers are fused using Kalman, Madgwick, and Complementary filtering methods (Wang et al., 2019; Worsey, Pahl, Espinosa, Shepherd & Thiel, 2021).

The increase in the diversity and complexity of the algorithms used in motion analysis offers advantages such as more precise results to researchers but limits the use of IMUs by people acting in the field. In a recent survey, it has been shown that one of the barriers to the use of sensor-based technologies is that the technology is not sufficiently recognized by coaches (Mooney et al., 2016). The same study showed that coaches prefer equipment that is easy to use, cheap and provides easy-to-understand data to perform technical analysis. Based on this information, this study aimed to determine the arm-stroke and kicking cycle durations utilizing the 1-axis acceleration data obtained from the IMUs, and test the validity of the method by comparing the results with those determined using the video images.

Method

Participants

Ten (5 male and 5 female) national-level swimmers participated in the study (See Table 1 for descriptive statistics). All swimmers have 8-10 years of racing experience. Since all four swimming techniques (butterfly, backstroke, breaststroke, and freestyle) were planned to be performed for the study, the participants were chosen as the swimmers competing in individual medley events (100m, 200m and 400m). The participants were informed verbally and written about the study and signed informed consent forms before the measurements. Individuals who had a health problem affecting swimming performance or who had undergone a medical operation within 6 months from the measurement date were not included in the study. Participants could leave the study at any time without stating any reason, and if they had a health problem during the measurements, they would be excluded from the study.

Table 1. Descriptive statistics of the participants.

				Butterfly		Backstroke		Breaststroke		Freestyle	
Gender	Age (year)	Height (m)	Weight (kg)	PBT (s)	TT (s)	PBT (s)	TT (s)	PBT (s)	TT (s)	PBT (s)	TT (s)
Male	19.6 ± 2.41	1.81 ±.03	81.2 ± 2.69	24.56 ± .46	28.22 ± .53	24.81 ± .45	28.53 ±.52	28.02 ± .57	32.22 ± .66	23.29 ± .41	26.78 ± .47
Female	18.2 ± .84	1.69 ± .04	60.76± 1.86	27.43 ± .43	31.54 ± .49	28.74 ± .86	33.05 ± .99	32.96 ± .88	37.91 ± 1.01	26.12 ± .38	30.04 ± .44

PBT = Personal best times; TT = Trial times (Trial times in all techniques are measured for 50 meters)

Experimental Procedure

All trials were carried out in a 50m indoor swimming pool with controlled water (27-28℃) and air (29-31℃) temperatures. Swimmers completed a 30-minute warm-up before starting the trials to prevent injury. In the warm-up, kicking, arm-stroke and swimming sets of 4 techniques were included. Ten minutes of the resting period was given at the end of the warm-up and the sensors were placed within this period.

Swimmers were asked to perform 2x50m with a push-off (in-water) start for each swimming technique and their performances were verbally requested to be %15 slower (calculated as the time before trials started) than the best 50m times. Dolphin kicks after the glide were not allowed for any technique. To prevent trials from being affected by fatigue, 5-minute active rests including low-pace swimming were given between trials. The trial had the closest time to 85% of their best performance included in the analyses.

Images (1280x720p) of the trials were recorded via two (one under and one above the water) action cameras (Sony, FDRX1000V, Japan) mounted on a carrier. The underwater camera was placed at a depth of 80 cm from the water surface, and the above-water camera was placed at a height of 100 cm from the water surface. In all trials, images were recorded from the right side of the swimmer at an angle of 90 degrees to the swimmer's axis of motion. The carrier was pulled in line with the swimmer during the trials by an experienced researcher, and the cameras on it were ensured to take the clearest imagme possible. Four IMUs with a measurement range of ±16 g (ActiGraph, Link GT9X, USA) were placed on the participants' bodies. Two of them were placed on the posterior side of wrists (on the styloid process of ulna and Lister's tubercule of radius bones), and two on the ankles (on the 3cm superior of lateral malleous) as shown below (Figure 1).

In all trials, cameras were operated at a recording speed of 100 frames per second, and IMUs at a data acquisition rate of 100 samples per second. Cameras and IMUs were synchronized before all trials.

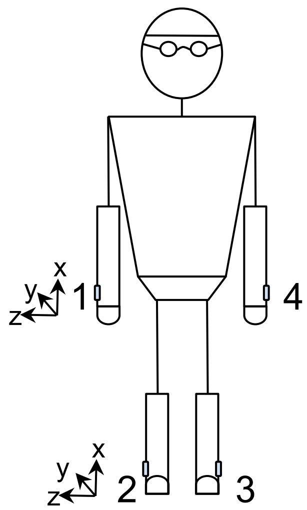


Figure 1. Locations and axes of IMUs on the swimmer's body

Data Analysis

The y-axis acceleration data were used to determine arm-stroke and kicking cycles and their durations. The sensor coordinate system was used in the calculations. For this reason, it should be kept in mind that the positions and orientations of the sensors changed due to arm and leg movements. For butterfly and freestyle, the peak was caused by the impact at the entries; for backstroke, the change of direction in the acceleration data as the hand goes into pronation; for breaststroke, the peak at the catch was accepted as the beginning point of the arm-stroke cycles. For the butterfly, backstroke and freestyle kicks, the peaks at transition points between the down and up-beat phases; for breaststroke kicks, the peaks at transition points (catch) between out and in-sweep phases were accepted as the beginning points of the cycles. The catch points for arm-strokes and kicks defined by (Maglischo, 2003) were used for all strokes.

All acceleration data was attenuated by a third-order low pass filter with a 2Hz cut-off frequency and plotted using KST2 data processing-plotting software. The filtered data were transferred to MS Excel software (Version 2206) with the time variable in column A and the acceleration variable in column B. By using the equation =IF(AND(B2>C2,B3>B2,B3>B4), "Peak",""), the peaks on the data set were determined. A threshold value is written in cell C2 if needed. Thus, peaks larger and smaller than certain values can be detected in an arm-stroke or kicking cycle. Other than MS Excel, any software that can recognize "if" and "and" commands can be used to detect peaks. Two experienced researchers who carried out video-based motion analysis studies examined the video recordings using the Tracker (O.S.P, Ver. 5.1.5) software and digitized the beginning point of the arm-stroke and kicking cycles. Incomplete arm-stroke cycles seen in the last part of the pool, that is, in the finishing phase, were not included in the analysis.

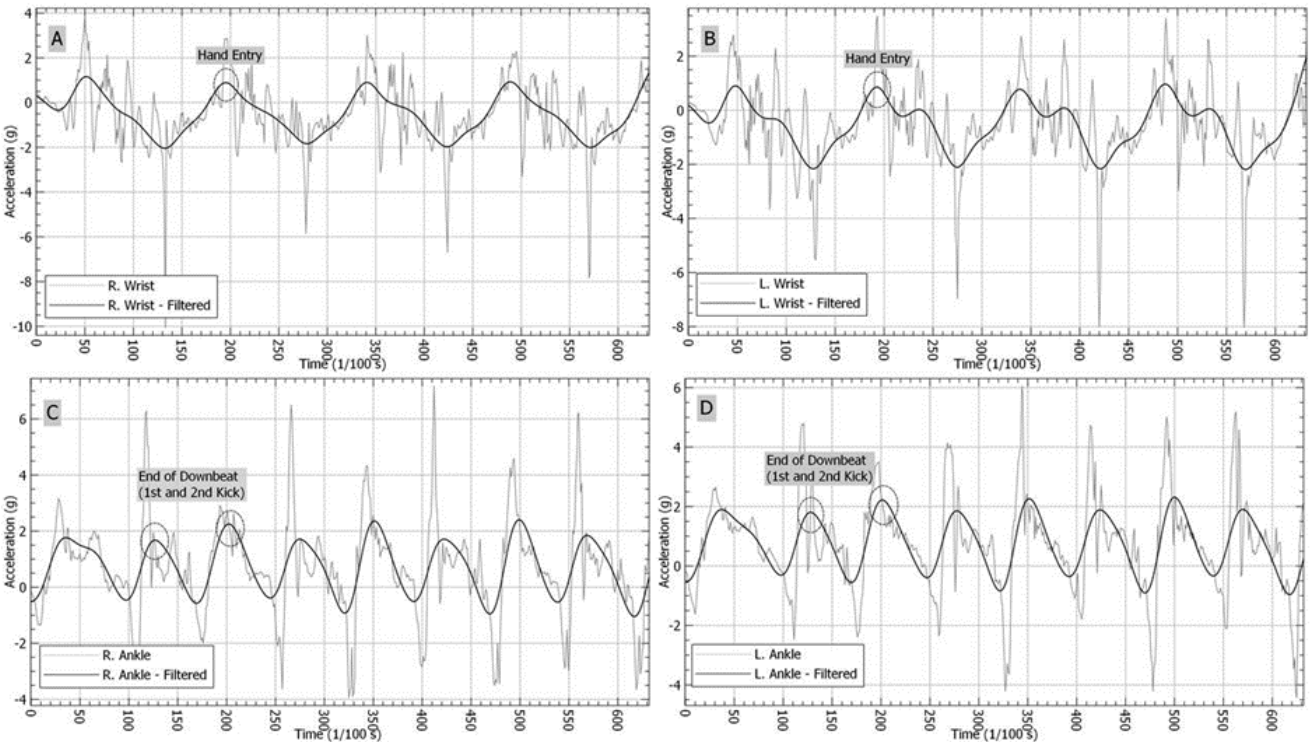
All durations of arm-stroke and kicking cycles for all swimming techniques included in statistical analyses. It was decided to examine the cycles according to gender, since the number of cycles and durations were significantly different, which would increase the variance in statistical calculations. Bland-Altman method were used to examine the agreement between the data obtained by two measurement methods. Mean difference ±1.96 standard deviations (95% confidence interval) were accepted as limits of agreement for all data couples. One-Sample T-Tests were used to test whether the difference between the data differed significantly from the “0” to ensure an objective decision. The normality of the differences was tested with the Kolmogorov-Smirnov Test. The level of significance was determined as .05 for all tests. Statistical tests were carried out using IBM SPSS Statistics (Version 24 for Windows; IBM, NY, USA)

Ethical Approval

The ethics committee approval for this study was given by Nevsehir Haci Bektas Veli University Ethics Committee (document no: 2022.03.31-2100081420). The study was carried out in line with the Helsinki Declaration.

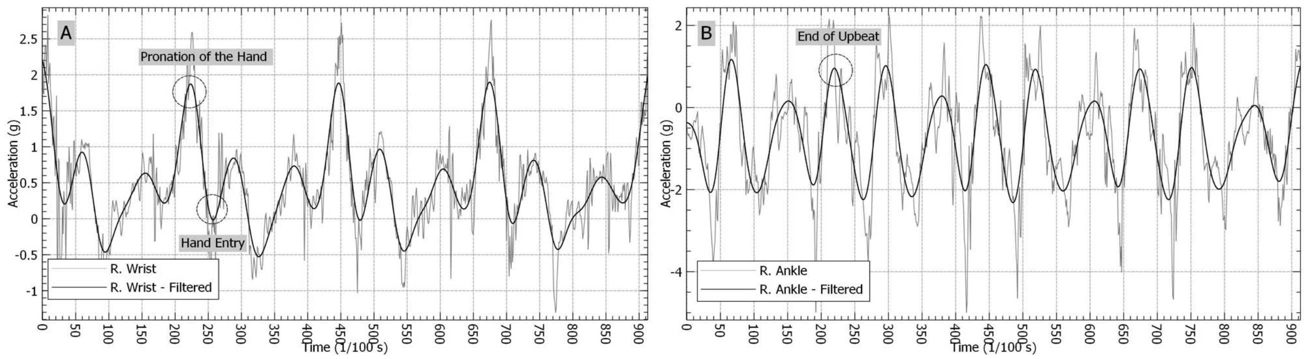
Findings

Due to a large number of figures (a total of 160 considering both sides of the body, ankles and wrists) and long time periods (approximately 30 seconds), it was not possible to present all in a way that covers the whole trials. For this reason, figures with summary data of randomly selected trials were given. Time-series of 3-4 arm-stroke cycles and corresponding kicking cycles are given in the figures in raw and filtered form. The time window selected while creating the figures belongs to the trials approximately between the 25th and 35th meters, and the x-axis shows the time in 1/100 seconds, and the y-axis shows the acceleration in g. In Figure 2, acceleration data collected by all IMUs are given for the butterfly. Subsequently, in Figures 3-5, acceleration data collected only by the IMUs on the right side of the body are given for backstroke, breaststroke and freestyle. In addition, the points accepted as the beginning of the cycles are marked in the Figures.



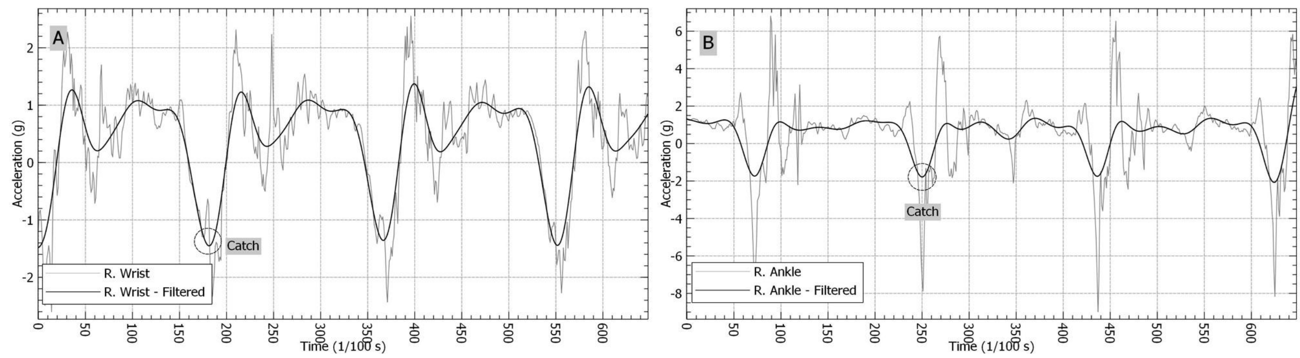
A = Arm-strokes of right arm; B = Arm-strokes of left arm; C = Kicks of right leg; D = Kicks of left leg

Figure 2. Raw and filtered acceleration data of butterfly arm-strokes and kicks



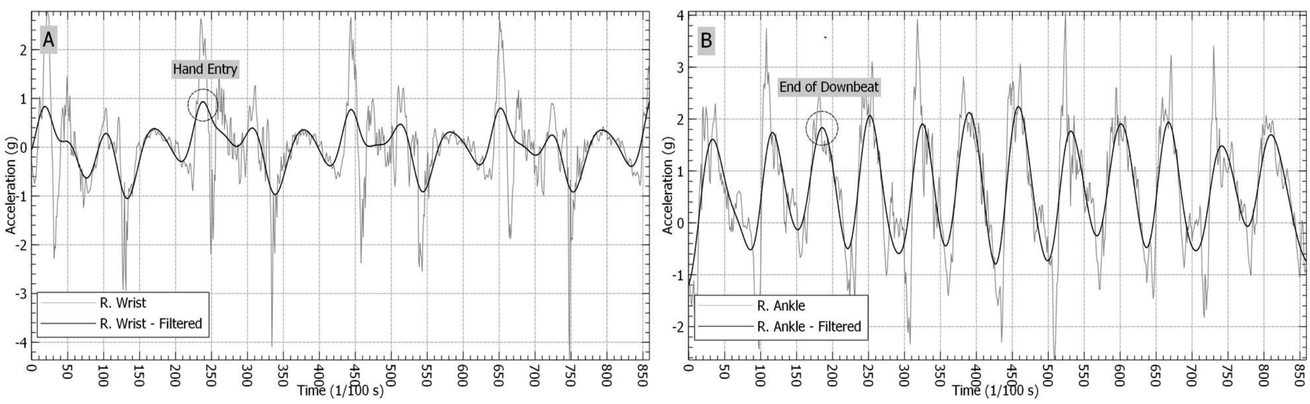
A = Arm-strokes of the right arm; B = Kicks of the right leg

Figure 3. Raw and filtered acceleration data of backstroke arm-strokes and kicks



A = Arm-strokes of the right arm; B = Kicks of the right leg.

Figure 4. Raw and filtered acceleration data of breaststroke arm-strokes and kicks



A = Arm-strokes of right arm; B = Kicks of right leg

Figure 5. Raw and filtered acceleration data of freestyle arm-strokes and kicks

Almost all of the differences in arm-stroke and kicking cycle durations were within the limits of agreement, between the ±1.96 standard deviation. Only four differences in the arm-stroke cycle durations of the men's butterfly and four in the kicking cycle durations of the women's butterfly were outside the limits of the agreement. Regardless of gender and swimming stroke, the average biases for all arm-stroke and kicking cycle times were quite small. As a matter of fact, the results of One-Sample T-Tests indicated that the differences between arm-stroke (Table 2) and kicking cycle (Table 3) durations were not statistically different from 0 (*p*>.05 for all).

Table 2. Descriptive statistics of arm-stroke cycles and one-sample t-test results.

Stroke Type	Gender	IMU			Video		One-Sample T-Test			
		n	*M*	*SD*	*M*	*SD*	*M. Diff*	*SD*	*t*	*p*
Butterfly	Female	110	132.00	5.19	132.00	5.99	0.66	3.70	1.88	0.06
	Male	84	139.95	5.82	140.06	6.57	-0.11	2.97	-0.33	0.74
Backstroke	Famale	74	222.91	6.75	223.65	7.55	-0.74	3.42	-1.87	0.07
	Male	56	222.41	4.69	222.82	6.34	-0.41	3.82	-0.81	0.42
B.stroke	Female	81	168.56	6.00	167.80	7.17	0.76	3.36	1.96	0.05
	Male	75	182.41	6.20	182.85	7.36	-0.44	4.09	-0.93	0.36
Freestyle	Female	86	195.40	7.95	195.74	9.05	-0.35	3.90	-0.83	0.41
	Male	62	166.67	6.61	165.80	7.28	0.87	4.56	1.51	0.14

Arm-Stroke Cycle Duration (1/100s)

Table 3. Descriptive statistics of kicking cycles and one-sample t-test results.

Stroke Type	Gender	IMU			Video		One-Sample T-Test			
		n	*M*	*SD*	*M*	*SD*	*M. Diff*	*SD*	*t*	*p*
Butterfly	Female	220	69.78	3.43	70.18	4.79	-0.41	3.33	-1.80	0.07
	Male	168	70.37	5.86	70.31	6.64	0.06	3.43	0.23	0.82
Backstroke	Female	296	64.23	4.72	63.98	6.10	0.25	3.82	1.14	0.26
	Male	268	75.52	7.67	75.25	8.31	-0.19	2.40	-1.27	0.21
B.stroke	Female	81	167.30	7.00	168.09	8.74	-0.78	4.22	-1.64	0.11
	Male	75	183.63	7.04	183.41	7.22	0.21	3.29	0.56	0.58
Freestyle	Female	366	59.31	5.11	59.33	6.67	-0.02	4.87	-0.08	0.93
	Male	298	69.17	4.09	68.95	6.22	0.22	4.67	8.81	0.42

Kicking Cycle Duration (1/100s)

Discussion

The primary aim of this study is to enable the coaches working in the field to benefit more from the IMUs, which are frequently used in recent research studies to examine the kinematic and temporal variables in swimming, and thus to make a positive contribution to the performance of the swimmers. Considering the number of participants, it was decided to conduct this study as a pilot study. For this aim, 4 IMUs were placed on the wrists and ankles of 10 competitive swimmers and they were asked to swim 50 meters at speeds corresponding to 85% of their best time in each technique. Only the y-axis acceleration data was included in the analysis, and the duration of the arm-stroke and kicking cycles of the swimmers was determined after a very simple filtering process. Although techniques visually seem similar, results of studies using IMUs indicate that swimmers draw quite different acceleration profiles from each other even when swimming the same technique.

From this point of view, it has been tried to choose the points that can easily be seen in the acceleration data as the beginning and end of the arm-stroke and kicking cycles, which are not greatly affected by the technique of the swimmer and previously defined in the literature. In our study, we chose the peaks formed during the entry of the hand into the water as the starting and ending points of the arm-stroke cycle of the butterfly and freestyle. Although it is quite easy to distinguish these peaks in the freestyle and butterfly due to the peaks, it may be a bit difficult to distinguish the peak that occurs during the entry of the hand in the backstroke. For this reason, the peak that occurs when the IMU changes orientation during pronation of the hand, which we clearly observed in the data of all participants, was given as an alternative to the entry of the hand in the backstroke arm-stroke acceleration graph.

There are studies in the literature reporting that the arm-stroke and kicking cycle durations calculated from the data obtained by the two measurement methods are not statistically different from each other (Callaway, 2015; Stamm, James & Thiel, 2013). In addition, inspiring results were obtained in trials with a combination of different measurement tools such as GPS+Accelerometer (Beanland, Main, Aisbett, Gastin & Netto, 2014). It is seen that advanced techniques such as neural networks and deep learning have started to be used in recent scientific study examples that include IMUs. By using these techniques, the recognition of the techniques and the phases of the techniques has become possible with high accuracy (Tarasevičius & Serackis, 2020; Worsey et al., 2021). Although all these studies have made very valuable contributions to the field, the fact that the algorithms and stages used in the process of reaching the result are very difficult to implement by the coaches working in the field prevents the widespread use of IMUs. It seems that it will take some time for devices using algorithms such as neural networks or deep learning to be released with an interface that can be easily used by coaches, without the need for specialized software.

Conclusion

Our research shows that accelerometer data alone without fusion with other sensors or processed with complex algorithms and the need for bulky video-based analysis systems can be used practically in swimming by coaches for timing, counting strokes, identification and measurement of time durations of various intervals, periods and phases.

Funding

This research has no funding.

Conflict of Interest

The authors report no conflict of interest.

Author Contributions

Research Idea: UÖ, KÖ; Research Design: UÖ, KÖ; Analysis of Data: UÖ, KÖ; Writing: UÖ, KÖ; Critical Review: UÖ, KÖ

References

1. **Ahmad, N., Ghazilla, R. A. R., Khairi, N. M., & Kasi, V.** (2013). Reviews on various inertial measurement unit (IMU) sensor applications. *International Journal of Signal Processing Systems, 1*(2), 256-262.
2. **Bächlin, M., & Tröster, G.** (2012**).** Swimming performance and technique evaluation with wearable acceleration sensors. *Pervasive and Mobile Computing, 8*(1), 68-81.
3. **Beanland, E., Main, L. C., Aisbett, B., Gastin, P., & Netto, K.** (2014). Validation of GPS and accelerometer technology in swimming. *Journal of Science and Medicine in Sport, 17*(2), 234-238.
4. **Callaway, A. J.** (2015). Measuring kinematic variables in front crawl swimming using accelerometers: A validation study. *Sensors, 15*(5), 11363-11386.
5. **Callaway, A. J., Cobb, J. E., & Jones, I.** (2009). A comparison of video and accelerometer based approaches applied to performance monitoring in swimming. *International Journal of Sports Science & Coaching, 4*(1), 139-153.
6. **Ceseracciu, E., Sawacha, Z., Fantozzi, S., Cortesi, M., Gatta, G., Corazza, S., & Cobelli, C.** (2011). Markerless analysis of front crawl swimming. *Journal of Biomechanics, 44*(12), 2236-2242.
7. **Davey, N., Anderson, M., & James, D. A.** (2008). Validation trial of an accelerometer-based sensor platform for swimming. *Sports Technology, 1*(4-5), 202-207.
8. **Engel, A., Ploigt, R., Mattes, K., & Schaffert, N.** (2021). Intra-cyclic analysis of the butterfly swimming technique using an inertial measurement unit. *Journal of Sport and Human Performance, 9*(2), 1-19.
9. **Engel, A., Schaffert, N., Ploigt, R., & Mattes, K.** (2022). Intra-cyclic analysis of the front crawl swimming technique with an inertial measurement unit. *Journal of Human Sport and Exercise*, 17(3), 667-682.
10. **Guignard, B., Rouard, A., Chollet, D., & Seifert, L.** (2017). Behavioral dynamics in swimming: The appropriate use of inertial measurement units. *Frontiers in Psychology, 8*, 383.
11. **Hamidi Rad, M., Gremeaux, V., Dadashi, F., & Aminian, K**. (2021). A Novel macro-micro approach for swimming analysis in main swimming techniques using IMU sensors. *Frontiers in Bioengineering and Biotechnology, 8*, 597738.
12. **Le Sage, T., Bindel, A., Conway, P., Justham, L., Slawson, S., & West, A.** (2010). Development of a real time system for monitoring of swimming performance. *Procedia Engineering, 2*(2), 2707-2712.
13. **Lennox, J. W., Rayfield, J., & Steffen, B.** (2006). *Soccer skills and drills. USA*: Human Kinetics.
14. **Magalhaes, F. A. d., Vannozzi, G., Gatta, G., & Fantozzi, S.** (2015). Wearable inertial sensors in swimming motion analysis: A systematic review. *Journal of Sports Sciences, 33*(7), 732-745.
15. **Maglischo, E. W.** (2003). *Swimming fastest. USA*: Human Kinetics.
16. **Marinho, D. A., Barbosa, T. M., & Neiva, H. P.** (2013). Swimming, running, cycling and triathlon. In *Routledge Handbook of Sports Performance Analysis* (pp. 454-481), ebook: Routledge.
17. **Monnet, T., Samson, M., Bernard, A., David, L., & Lacouture, P.** (2014). Measurement of three-dimensional hand kinematics during swimming with a motion capture system: a feasibility study. *Sports Engineering, 17*(3), 171-181.
18. **Mooney, R., Corley, G., Godfrey, A., Osborough, C., Newell, J., Quinlan, L. R., & ÓLaighin, G.** (2016). Analysis of swimming performance: perceptions and practices of US-based swimming coaches. *Journal of Sports Sciences, 34*(11), 997-1005.
19. **Mooney, R., Corley, G., Godfrey, A., Osborough, C., Quinlan, L., & ÓLaighin, G.** (2015). Application of video-based methods for competitive swimming analysis: a systematic review. *Sports and Exercise Medicine, 1*(5), 133-150.
20. **Nugent, F. J., Comyns, T. M., & Warrington, G. D.** (2017). Quality versus quantity debate in swimming: perceptions and training practices of expert swimming coaches. *Journal of Human Kinetics, 57*(1), 147-158.
21. **O'Reilly, M., Caulfield, B., Ward, T., Johnston, W., & Doherty, C.** (2018). Wearable inertial sensor systems for lower limb exercise detection and evaluation: a systematic review. *Sports Medicine, 48*(5), 1221-1246.
22. **Pansiot, J., Lo, B., & Yang, G.-Z.** (2010, June). Swimming stroke kinematic analysis with BSN*. Paper presented at the 2010 International Conference on Body Sensor Networks*, Biopolis, Singapore.
23. **Pérez, P., Llana, S., Brizuela, G., & Encarnación, A.** (2009). Effects of three feedback conditions on aerobic swim speeds. *Journal of Sports Science & Medicine, 8*(1), 30.
24. **Schaffert, N., Engel, A., Schlüter, S., & Mattes, K.** (2019). The sound of the underwater dolphin-kick: developing real-time audio feedback in swimming. *Displays, 59*, 53-62.
25. **Silvatti, A. P., Cerveri, P., Telles, T., Dias, F. A., Baroni, G., & Barros, R. M.** (2013). Quantitative underwater 3D motion analysis using submerged video cameras: accuracy analysis and trajectory reconstruction. *Computer Methods in Biomechanics and Biomedical Engineering, 16*(11), 1240-1248.
26. **Slawson, S., Justham, L., Conway, P., Le-Sage, T., & West, A.** (2012). Characterizing the swimming tumble turn using acceleration data. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 226*(1), 3-15.
27. **Stamm, A., James, D. A., & Thiel, D. V.** (2013). Velocity profiling using inertial sensors for freestyle swimming. *Sports Engineering, 16*(1), 1-11.
28. **Stamm, A., & Shlyonsky, I.** (2020, November). Freestyle swimming analysis of symmetry and velocities using a mems based imu: introducing a symmetry score*. Paper presented at the icSPORTS*, Budapest, Hungary.

29. **Tarasevičius, D., & Serackis, A.** (2020, April). Deep learning model for sensor based swimming style recognition. *Paper presented at the 2020 IEEE Open Conference of Electrical, Electronic and Information Sciences (eStream)*, Vilnius, Lithuania.
30. **Tolza, X., Soto-Romero, G., Fourniols, J.-Y., & Acco, P.** (2017). Preliminary study: IMU system validation for real-time feedback on swimming technique. *Computer Methods in Biomechanics and Biomedical Engineering, 20*(sup1), S203-S204.
31. **Wang, Z., Shi, X., Wang, J., Gao, F., Li, J., Guo, M., . . . Qiu, S.** (2019, October). Swimming motion analysis and posture recognition based on wearable inertial sensors. *Paper presented at the 2019 IEEE international conference on systems, man and cybernetics (SMC)*. Bari, Italy.
32. **Wilson, B. D.** (2008). Development in video technology for coaching. *Sports Technology, 1*(1), 34-40.
33. **Worsey, M. T., Pahl, R., Espinosa, H. G., Shepherd, J. B., & Thiel, D. V.** (2021). Is machine learning and automatic classification of swimming data what unlocks the power of inertial measurement units in swimming? *Journal of ports sciences, 39*(18), 2095-2114.
34. **Zhang, Z., Xu, D., Zhou, Z., Mai, J., He, Z., & Wang, Q.** (2017, October). IMU-based underwater sensing system for swimming stroke classification and motion analysis. *Paper presented at the 2017 IEEE International Conference on Cyborg and Bionic Systems (CBS)*. Benjing, China.