Original article

Title: The validity of a head-worn inertial sensor for measurements of swimming performance.

Titre: Validité d'un capteur inertiel porté à la tête pour mesurer les performances en natation.

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Running head: "Validity of the inertial sensor for swimming"

Key words: Micro-technology; measurement error; water sports

Abstract

The validity of the TritonWear® device to measure swimming performance was investigated, with a pre-determined analytical goal of 6%. Twenty youth swimmers completed a 100 m swim in a 25 m pool, swimming breaststroke or freestyle wearing the TritonWear® device, whilst being filmed above and below water with three cameras. 95% Limits of Agreement (95% LoA) and coefficient of variation (CV%) were used to calculate error. Systematic biases ($P < 0.05$) were found between the two systems only for distance per stroke during breaststroke. Freestyle metrics agreement ranged between 1.06 % and 10.40 % CV, except for distance per stroke (CV = 14.64 %), and time underwater (CV = 18.15 %). Breaststroke metrics ranged between 0.95 % and 13.74 % CV, except for time underwater (CV = 25.76 %). The smallest errors were found for split-times, speed, stroke-count and stroke-rate, across both strokes (all < 5% CV). The TritonWear® can be used for basic metrics of performance, such as split-time and speed but the error of more complex measurements, such as time underwater or turn-times, renders them unable to identify typical performance changes.

Résumé

La validité du dispositif TritonWear® pour mesurer les performances en natation a été étudiée avec un objectif analytique prédéterminé de 6%. Vingt jeunes nageurs ont réalisé une épreuve de 100 m dans une piscine de 25 m, en brasse ou en nage libre en portant le dispositif TritonWear®, tout en étant filmés au-dessus et en dessous de l'eau avec trois caméras. Les limites de concordance à 95% (LoA à 95%) et le coefficient de variation (CV%) ont été utilisés pour calculer l'erreur. Des biais systématiques ($p < 0,05$) ont été trouvés entre les deux systèmes uniquement pour la distance parcourue par coup de bras en brasse. La concordance des métriques en nage libre variait entre 1,06% et 10,40% du CV, sauf pour la distance par coup de bras (CV = 14,64%) et le temps passé sous l’eau (CV = 18,15%). Les valeurs pour la brasse

variaient entre 0,95% et 13,74% du CV, sauf pour le temps passé sous l'eau (CV = 25,76%). Les plus petites erreurs ont été trouvées pour les temps intermédiaires, la vitesse, le nombre de coups de bras et la fréquence des coups de bras, pour les deux nages (tous <5% de CV). Le TritonWear® peut être utilisé pour les mesures de performance de base, telles que le temps intermédiaire et la vitesse, mais l'erreur sur des paramètres plus complexes, telles que la durée d'immersion ou les temps de virage, ne permet pas d'identifier des modifications de ces paramètres.

Introduction

The margins of success and failure in competitive pool swimming are small, particularly in sprint (< 400 m) events. For example, there are approximately 6% differences in velocity between qualifiers and non-qualifiers of world championships (Takagi et al., 2004) and even smaller differences (0.5 – 3 %) between 1st and 2nd place in 100 m Olympic finals (https://www.olympic.org/rio-2016/swimming) or after training programme manipulation (Mujika et al., 1995; Mujika et al., 2002). The 6% differences between qualifiers and non-qualifiers (Takagi et al., 2004) is closely aligned with the training-induced performance changes across key performance metrics. Therefore, a 6% change in performance provides the most relevant differentiation of ability levels among competitive swimmers and is a change that can be achieved owing to training. This threshold therefore represents a reasonable 'analytical goal' (Atkinson & Nevill, 1998). Analytical goals are formulated to determine the maximal level of measurement error that can be permitted by an investigator when using a device to detect changes in performance. As such, the accuracy of testing equipment must be sufficient to recognise anticipated changes in performance, which should be determined prior to evaluation of its measurement error (analytical goals).

Video- or sensor-based data devices are typically used to quantify swimming performance (Beanland et al., 2014). Video analyses are considered to be the 'gold standard' method (Ceseracciu et al., 2011) and are the most commonly used (Gourgoulis et al., 2008; Smith et al., 2002). Despite this, video analysis techniques are complex and rely on the technical expertise of the user (Knudson, 2007). Furthermore, their lower sampling rate 25-30 Hz is likely to limit the accuracy of performance metrics during high-speed movements, such as stroke rate or during turning manoeuvres. Wearable and water-proof microelectromechanical systems (MEMS) provide a possible alternative to video analysis techniques (Callaway et al., 2009; Dadashi et al., 2013; Ohgi et al., 2003). An example of this is the 'TritonWear®' device, which claims to accurately measure speed and stroke efficiency metrics using a head-mounted unit - the fitting of which causes less proprioceptive disruption than limb- or torso-worn devices (Lecoutere & Puers, 2014).

The TritonWear® technology measures a number of swimming performance metrics, such as split-time, stroke count, speed, stroke rate, distance per stroke, turn-time and time underwater (Lehary, 2015). Indeed, it is relevant to provide accurate measurements of these kinematic variables, since success in swimming performance is largely explained by their combination (Barbosa et al., 2010). Whilst others have investigated the validity of a global positioning system-micro-technology (GPS) to quantify swimming performance metrics (Beanland et al., 2014), these devices were not purpose-built for monitoring swimming performance. As such limitations in the technology during water submersion, as well as raw sampling rate of GPS-derived measurements ($\leq$ 10 Hz) or the algorithmic treatment of raw MEMS signals on board these units appeared to preclude their application. For example, stroke count was unreported by Beanland et al. (2014) during freestyle swimming, owing to cumulative noise accrued by the accelerometer during this stroke. Thus, the validity and reliability of a miniaturised swimming-specific device intended for these key performance measurements is currently unknown and could be used to replace more rudimentary chronometry, video methods or non-specific micro-technology commonly used by swimming coaches.

The aim of this study was to evaluate the validity of the TritonWear® device to measure selected swimming performance metrics in comparison to a reference underwater video camera system among competitive youth swimmers. For the current analysis, we adopted a conservative *a-priori* analytical goal (see Atkinson & Nevill, 1998) that approximated the typical changes observed in performance (split-time or speed) over a season among the current or athletes in the literature of 6% (Takagi et al., 2004). The error (i.e. noise) between devices for these variables should, therefore, permit the detection of signal changes of this magnitude.

Methods

Design and procedure

Participants completed a 100 m swim in an outdoor 25 m swimming pool (4 x 25 m), swimming either breaststroke or freestyle, wearing the TritonWear® device (The Triton Unit, firmware version 1.1.2, 50 Hz, TritonWear Inc.®, Ontario, Canada), whilst being filmed above and below water with fixed video cameras to evaluate validity. The two stroke-types were selected as they were the two stokes used in competition by the current participants.

Participants

Ten male and ten female (total *n* = 20) competitive national swimmers (age 16 ± 3 years; stature 170 ± 15 cm; body mass 61.5 ± 14.7 kg) and their parent/guardian provided written informed consent to participate in the study. All participants took part in all trials. Institutional ethical approval was granted for this study.

TritonWear® and Video Systems

The components of the TritonWear® waterproof sensor unit include: a 9-axis inertial measurement unit; a 3-axis digital accelerometer; a 3-axis digital gyroscope; a 3-axis digital magnetometer; a micro-controller; a wireless module to transmit calculated metrics to the hub; a clock to synchronise timing; and a lithium ion polymer battery with an internal battery charging unit. The tracker reads oscillation data in three axes from the accelerometer and gyroscope. The device measures 62 x 54 x 19 mm, weighs 51 g and is connected to the back of the swimming goggle strap (Figure 1). The transmitted data were later analysed using the manufacturer's software (TritonWear Insights, Ontario, Canada).

******Insert figure 1 here******

Various metrics were analysed from the TritonWear® device. The start of each trial was automated by the device as the internal gyroscope and accelerometer detect the swimmers motion as they transition their head from a vertical to a horizontal position. As the swimmer pushes off the wall, an increase in acceleration is detected by the accelerometer (sampling at 50 Hz), triggering an internal timer. The completion of a swim is determined by the following characteristics in the signal from the sensors: an acceleration spike as the swimmer reaches the wall, the transfer from horizontal to vertical head position, and finally, the decrease in oscillatory signals being detected by the device.

The TritonWear® device calculated all variables using the internal accelerometer and gyroscope, which read and classify the oscillatory signals that are produced during swimming. The push-off from the wall at the start of a swim was detected by the accelerometer, which triggered a timer. Stroke type and stroke count were determined by the gyroscope, which sensed the swimmers' angular velocities through three axes. The angular position for each axis was determined using the numerical Euler method, which read the pitch, yaw and roll of the swimmers' head as they moved through the water. Turn-time (s) was measured by the gyroscope; the timer started at the downwards movement of the swimmer's head for freestyle and the rotation movement in an open turn for breaststroke, and ended when the swimmer's feet touched the wall, also capturing the end of a split. Time underwater (s) was calculated by taking the time between the push-off from the wall (accelerometer), and the breakout event of the head prior to the first stroke (gyroscope). Distance per stroke (m) was calculated by (length of pool (m) – distance underwater (m)) / number of strokes. Speed (m/s) was determined by calculating linear acceleration data and the change in time (acceleration x time) to determine the average velocity of each swimmer for each length of the pool (m). Stroke rate (n/min) was measured by subtracting the average time underwater from the average split-time, which is then divided by the average number of stroke cycles in a length. For freestyle, one left hand stroke and one right hand stroke equalled one stroke cycle. For breaststroke, each stroke is counted as one stroke cycle. Once cessation of swimming was determined by the accelerometer, the timer stopped and an overall time for the swim (split-time; s) was calculated.

Three cameras were used, in combination, to track the performance of the swimmers. This comprised two underwater cameras (WallMount Cam, 1080p, 30 frames/s, SwimPro®, RJB Engineering, New South Wales, Australia) and one iPad 2 (1080p, 30 frames/s, Apple Inc., California, USA). Above water video was recorded using the iPad 2 and CoachesEye® (TechSmith Corporation, Michigan, USA) analyses software. The underwater video cameras were left running throughout the trials, whereas individual videos of swimmers were captured using the iPad. The start and end of each trial was indicated by one investigator on the video, so that it could be synchronized *post-hoc* with the TritonWear® recording analyses. One experienced (> 5 years) investigator, with training and qualifications in performance analysis, was responsible for video-based assessments. The operator had used the performance metrics and the associated working definitions previously. Their intra-operator error for freestyle and breaststroke video data ranged between 1.01 % and 5.89 % CV. Table 1 provides the criteria that were used to ensure that each variable was objectively evaluated.

Table 1. Video analysis criteria.

Variable	Criteria
Split-time (s)	Clock started when the feet of the swimmer left the wall, to the time that the hand touched the wall on the final length. This figure was divided by four to give the average split-time.
Stroke count (*n*)	Freestyle: Each hand entry was recorded as one stroke, therefore one hand entry from each limb was counted as two strokes. Breaststroke: Each stroke was counted as one stroke.
Speed (m/s)	Average split-time was divided by the pool length (25 m).
Stroke rate (*n*/min)	The average time underwater was subtracted from the average split-time. This figure was then divided by the average number of stroke cycles in a length and expressed in minutes.
Distance per stroke (m/stroke)	The length of the pool - distance underwater / number of strokes identified.
Turn-time (s)	Freestyle: timing of the freestyle turn started when the head moved forwards and down, signalling the beginning of the swimmers turning action. The timer was stopped when the swimmer's feet hit the wall following the turn. Breaststroke: timing of the breaststroke turn started when the hands first touched the wall, signalling the beginning of the swimmers turning action. The timer was stopped when the swimmer's feet hit the wall prior to push-off.
Time underwater (s)	Timer started as the athlete's feet left the wall, timer stopped at first sight of the swimming cap above the surface of the water. Time underwater does not include turn-time.

Statistical analyses

Validity was assessed using a 95 % Limits of Agreement (95% LoA; (Atkinson and Nevill, 1998)) and coefficient of variation (CV%; (Hopkins, 2000). The current paper adopted an analytical goal of 6% and based its interpretations on the CV technique. The 95% LoA was provided for alternative interpretations among readers of the manuscript. Paired sampled *t*-tests were used to calculate bias between the TritonWear® device and video-based system. Statistical significance was set at $P < 0.05$ and adjusted for all dependant variables using a Bonferroni correction.

Results

The data (mean ± SD), CV% and 95% LoA for comparisons of the two devices are shown in Table 2. Comparison of the TritonWear® device against video analysis demonstrated no systematic biases ($P > 0.05$) for the freestyle stroke. For breaststroke, distance per stroke ($t_{(9)} = -4.14$, $P = 0.003$) showed systematic biases, while all other metrics did not ($P > 0.05$) (Table 2).

Table 2. Validity of TritonWear® data against video analysis data (n = 20).

Validity Data	TritonWear (mean ± s)	Video (mean ± s)	95% LoA	CV (%)
Freestyle				
Split-time (s)	17.45 ± 2.34	17.47 ± 2.44	-0.021 ± 0.51	1.06
Stroke count (n)	19.3 ± 1.77	19.3 ± 1.77	0.00 ± 1.31	2.44
Speed (m/s)	1.41 ± 0.19	1.45 ± 0.17	-0.041 ± 0.21	5.53
Stroke rate (n/min)	1.49 ± 0.22	1.55 ± 0.21	-0.065 ± 0.13	3.01
Distance per stroke (m)	1.13 ± 0.29	1.19 ± 0.10	-0.065 ± 0.47	14.64
Turn-time (s)	1.12 ± 0.13	1.13 ± 1.18	-0.003 ± 0.32	10.40
Time underwater (s)	2.72 ± 0.60	2.54 ± 0.28	0.185 ± 1.32	18.15
Breaststroke				
Split-time (s)	21.92 ± 2.22	21.88 ± 2.23	0.041 ± 0.57	0.95
Stroke count (n)	10.70 ± 2.06	10.8 ± 1.93	-0.1 ± 1.45	4.86
Speed (m/s)	1.14 ± 0.14	1.15 ± 0.11	-0.01 ± 0.08	2.79
Stroke rate (n/min)	1.56 ± 0.11	1.62 ± 0.14	-0.06 ± 0.17	3.77
Distance per stroke (m)	1.51 ± 0.19	1.95 ± 0.27	-0.44 ± 0.66*	13.74
Turn-time (s)	1.56 ± 0.23	1.36 ± 0.13	0.19 ± 0.52	12.91
Time underwater (s)	4.89 ± 2.06	4.53 ± 0.89	0.36 ± 3.35	25.76

Note: LOA = 95% limits of agreement; CV = coefficient of variation. Significantly different ($P < 0.05$); *Statistical significance ($P < 0.05$).

Freestyle metrics ranged between 1.06 % and 10.40 % CV, except for distance per stroke (CV = 14.64 %), and time underwater (CV = 18.15 %). Freestyle 95 % LoA metrics ranged between -0.065 ± 0.13 and 0.185 ± 1.32. Breaststroke metrics ranged between 0.95 % and 13.74 % CV, except for time underwater (CV = 25.76 %). Breaststroke 95 % LoA metrics ranged between -0.01 ± 0.08 and 0.36 ± 3.35 (Table 2).

Discussion

The main finding of this study was that the TritonWear® device did not systematically differ ($P > 0.05$) from the video-based system for most variables, besides distance per stroke in the breaststroke. The CV values for split-time, speed, stroke-rate and stroke-count were all <5% across both stroke types. As such, the error between the devices is smaller than the analytical goal of 6%, providing a favourable signal-noise ratio, thus indicating that the Tritonwear® device is valid for these measured variables. This means that an athlete could wear the device for 100 m training or competition and receive a split-time, speed or stroke-based metric that would agree with the reference system. However, based on the wide LoA and CV values for a number of other variables (turn-time, time underwater and distance per stroke), the degree of random error relative to the analytical goal of 6% questions their validity, leaving athletes unable to detect performance changes using this device.

There is opportunity for both biological error (that of the human operator) and technical error (that of the device) to affect the results of both systems used. The video-based system relies upon certain factors, such as the quality of the synchronised videos, the ability of the human eye to identify the start and end of a performance and the objectivity of the definitions used to guide the human investigator. Given that the split-time definitions were identical between devices and the investigators identified each variable in slow-motion (frame by frame), it is most likely that the different technical specifications account for the small variations in basic measurements of time and speed. For example, the different frame/sampling rates between techniques (30 Hz frame/s *vs.* 50 Hz MEMS on the TritonWear®) mean that the investigator might not be able to identify the exact time-point that the feet leave the wall, or reach the other end, with the equal resolution whilst using the video system. An accumulation of these discrepancies would lead to larger overall error across the 100 m swim duration. In addition to this, there are a variety of on-board algorithms that correct for error in the TritonWear® device, including advanced Kalman Filtering, that has capacity to correct for so-called 'drifts' based on recent historical information, such as previous velocity. The accelerometry-derived calculation of speed and iterative filtering processes, therefore, provide an advantage to the TritonWear® relative to the video-based system, alongside its ease of application and real-time feedback options for the swimmer.

The poorer agreement found for the more complex variables, such as time underwater and distance per stroke can be explained by technical error. Naturally, these variables require further computation and include input from a variety of sensors, at a higher frequency. For example, time underwater was the most variable comparison and requires the consistent recognition of two key events: i) push-off from the wall and ii) surfacing. These two events use two separate miniaturised systems; the accelerometer and gyroscope, respectively. Recognition of these discrete events presumably requires some achievement of a predicted threshold value, as well as their temporal synchronisation. A scenario where the athlete pushed off the wall with poor technique, or prematurely raised their head relative to their body, would be discordant with the expected technical 'model' of performance. Based on the above, there are a variety of both hardware and algorithmic degrees of freedom, which appear to have accumulated in the TritonWear® device and resulted in measurement errors that are likely to preclude its application with athletes in order to recognise changes in underwater time. This is important to consider, as underwater time is an established predictor of performance in competitive pool swimming (Vantorre et al., 2014) and, therefore, would be a useful tool for athletes to monitor their progress during training. The video-based systems might be more labour-intensive but do not suffer these same technical problems.

This study is not without limitations. For example, we were unable to access the raw signal of the inertial sensors or the proprietary underlying algorithms, thus restricting our ability to fully interrogate the signal processing or explore other methods of stroke analysis (see Dadashi et al., 2015). This would be worthwhile, since the most erroneous measurements were those with highest technical demand. Furthermore, the current analysis was constrained to 100 m distances. Drift errors are more common while using IMUs across longer time periods. However, the Kalman Filter used by the Tritonwear® was designed to correct for drift errors and might partially remove this source of measurement noise, yet this requires further analysis in future research. Finally, the video technique used was based on the performance of a single operator and might be less repeatable among different users. The subjectivity of the technique that is inevitably introduced when using human operators and poses a problem that can be overcome by adopting automated measurement systems.

In conclusion, the TritonWear® device can be used by athletes or swimming practitioners for basic metrics of performance, such as split-time, speed, stroke-rate and stroke-count. However, the error for time underwater and distance per stroke in comparison to a reference system, question the TritonWear® system's capacity to validly record these values.

Conflict of interest

No potential conflict of interest is reported by the authors.

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Author contributions

All authors (MW,JB,JT,OJ,SP,LH) contributed to the conception and design of the study, acquisition of data, analysis and interpretation of data, drafting the article, revising it critically for important intellectual content and final approval of the version submitted.

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Figure

Figure 1. Placement of TritonWear® device fitted directly inferior to the inion, on the occipital bone.