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Validation of GPS and accelerometer technology in swimming

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ABSTRACT

Objectives: To evaluate the validity of an integrated accelerometer and Global Positioning System (GPS) device to quantify swimming kinematics variables in swimming.
Design: Criterion validation study.
Methods: Twenty-one sub-elite swimmers completed three 100 m efforts (one butterfly, breaststroke and freestyle) in an outdoor 50 m Olympic pool. A GPS device with an integrated tri-axial accelerometer was used to obtain mid-pool velocity and stroke count of each effort. This data was compared to velocity and stroke count data obtained from concurrently recorded digital video of the performance.
Results: A strong relationship was detected between the accelerometer stroke count and the video criterion measure for both breaststroke ($r > 0.98$) and butterfly ($r > 0.99$). Also, no significant differences were detected between the GPS velocity and video obtained velocity for both freestyle and breaststroke. There was a significant difference between the GPS velocity and criterion measure for butterfly. Acceptable standard error and 95% limits of agreement were obtained for freestyle (0.13 $m\,s^{-1}$, 0.36 $m\,s^{-1}$) and breaststroke (0.12 $m\,s^{-1}$, 0.33 $m\,s^{-1}$) compared to butterfly (0.18 $m\,s^{-1}$, 0.50 $m\,s^{-1}$). Relative error measurements ranged between 10.2 and 13.4% across the three strokes.
Conclusions: The integrated accelerometer and GPS device offers a valid and accurate tool for stroke count quantification in breaststroke and butterfly as well as measuring mid-pool swimming velocity in freestyle and breaststroke. The application of GPS technology in the outdoor training environment suggests advantageous practical benefits for swimmers, coaches and sports scientists.

1. Introduction

Modern competitive swimming is highly reliant on the quantification and assessment of swimming performance to monitor training load, understanding athlete progression, identify talent and critique performance.[1–4] Swimming performance can be quantified in many ways but the specific kinematics variables of swimming performance such as a swimmer's velocity,[1] acceleration,[2] stroke rate,[1] stroke length[1] and stroke count[3] have been shown to correlate to competition success. Coaches, sports scientists and athletes remain highly dependent on quantifying these kinematic variables to guide performance enhancement.

On a day-to-day basis, kinematic variables of swimming performance are quantified by manual and self-reported ratings of stroke counts and the use of manually operated stopwatches.[3] This method of quantification, although quick and easy, may incorporate inconsistencies due to athlete bias or human error. To overcome this, video analysis was adopted to quantify kinematic variables during both training and competition and remains the method of choice for kinematics analysis in swimming despite the labour intensive and time consuming nature of the analysis process.[5]

To overcome some of the difficulties associated with video analysis in swimming, scientists have explored the use of wearable micro-sensor technology such as accelerometers and rate gyroscopes.[6,7] These sensors are able to accurately measure kinematic variables such as swimming stroke counts, providing a viable alternative to video analysis.[2] However, micro-sensor technology still lacks instantaneous velocity measurement, limiting current analysis of key kinematic variables such as stroke rate, stroke length and swimming velocity to average calculations across a 25 or 50 m lap.[6–8] Obtaining instantaneous velocity of an athlete is currently available for many land-based sports through the use of Global Positioning System (GPS) technology.[9–11] Recent evidence suggests GPS is a valid tool to measure linear human locomotion at slow movement speeds not dissimilar to elite swimming.[12,13] Since these devices integrate micro-sensor technology such accelerometers and rate gyroscopes, they may be highly applicable to quantifying kinematics in swimming.

The GPS operates off a network of satellites that continually orbit the earth and transmit radio frequency signals which travel from

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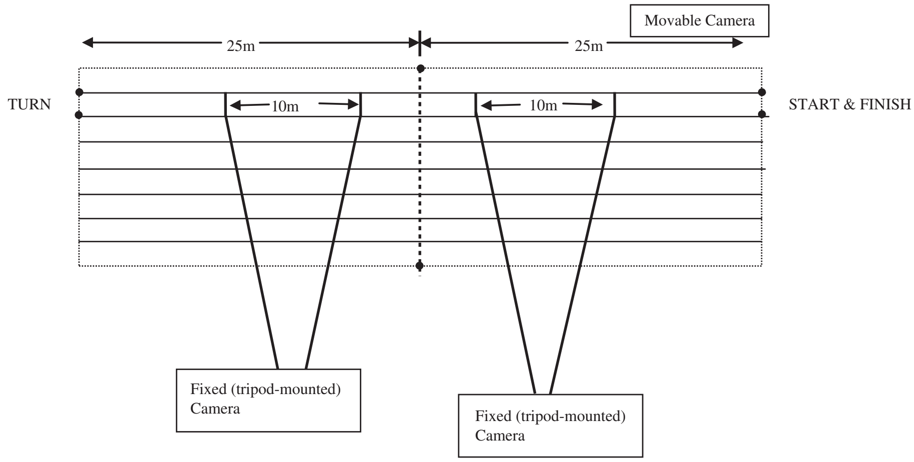

Fig. 1. Illustration of motion capture setup for each of the 100 m swimming trials.

the satellites to the GPS receiver.[12] Kinematics variables of distance and velocity are possible and give relevant information about an athlete's position, time, speed and direction to allow instantaneous quantification of movement during training and competition.[12–14] GPS devices are reliant on the clear line-of-sight to the orbiting satellites to obtain accurate kinematics data. This situation idealises the use of GPS in many land-based team sports and it is clear many of these sports are beginning to shift away from the labour-intensive video analysis to quantify kinematics of performance.[13] Using GPS devices in swimming may be more challenging as the athlete is partially submerged in the three prone Olympic strokes (freestyle, breaststroke and butterfly). The swimmer's head however, does stay unsubmerged for a long proportion of these strokes which may allow sufficient line-of-sight for the GPS to function. In support of this theory, GPS devices have also been used to quantify movement patterns of marine animals on, or close to the surface of the water.[15,16] This provides support for the application of GPS in a partially submerged sport such as swimming.

Wearable GPS and accelerometer devices are replacing the time consuming and laborious method of video analysis to quantify athlete kinematics in many land-based team sports.[13] This technology not only accurately quantifies slow, linear movement velocities not dissimilar to elite swimming but also incorporates other microsensors that have been shown to quantify swimming stroke counts. Therefore, the aim of this study was to assess the criterion validity of GPS and accelerometer technology to quantify the kinematic variables of stroke count and mid-pool velocity in the three prone strokes in swimming.

2. Methods

Twenty-one participants (12 males; age: 15 ± 3 years, height: 178 ± 9 cm, weight: 73 ± 14 kg and nine females; age: 16 ± 2 years, height: 169 ± 4 cm, weight: 63 ± 4 kg) were recruited to this study. Participant inclusion were based on regular involvement in high level swimming (at least five sessions per week) and having achieved an Australian State level qualifying time in the past swimming season (i.e. 2010/2011). Institutional ethical approval was obtained from the Deakin University Human Research Ethics Committee and informed written consent was obtained from each participant prior to the commencement of the study.

Participants were required to complete a 15 min swim-specific warm up administered by the researcher. Participants were then requested to exit the pool and a 10 Hz GPS device (minimax S4, Catapult Sports, Melbourne, Australia) was positioned on the head of each participant with the vertical axis of the accelerometer directly inferior to the inion, in line with the sagittal suture. A second swimming cap was placed over the GPS device to secure it for the duration of the trials. Participants completed three 100 m efforts (one butterfly, breaststroke and freestyle) in an outdoor 50 m Olympic pool. The head-worn GPS recorded velocity profiles of each 100 m effort while the integrated tri-axial accelerometer sampled the acceleration profiles of each effort at 100 Hz.

Video footage of each 100 m effort was captured at 25 Hz to obtain the criterion measures of stroke count and swim velocity (Fig. 1). A single, trolley mounted video camera (Canon mini DV-MD225, Japan) was manually trundled along the pool deck parallel to the swimmer and the footage from this camera was used to determine the stroke count of the effort. A further two fixed cameras captured footage of four mid-pool sections and this footage was used to determine the velocity of the effort. These fixed cameras did not provide full coverage of the entire length of the pool. As such, participants performed a single vertical jump prior to entering the pool, to facilitate post-processing synchronisation of the video and GPS/accelerometer data. Footage for calibrating the fixed cameras was collected prior to and at the completion of each data collection session, performed by placing a one metre calibration ruler (M391, Johnson Incorporated, USA) in the same plane as the participants' line of travel.

Velocity, acceleration and horizontal dilution of precision (HDOP) data, a measure of satellite geometry and as such accuracy of the GPS data[17] for each swim was downloaded from the GPS unit to a laptop personal computer via manufacturer supplied software (Logan Plus, version 4.7.1, Catapult Sports, Melbourne, Australia). In this software, acceleration profiles were manually assessed to obtain a stroke count for each swim. Further, acceleration profiles were also exported to Microsoft Office Excel 2007 (version 12, Microsoft, USA) where a five point moving average was applied to smooth the data and alogical statement (IF) was applied to detect and count the peaks in the acceleration profile and as such, automatically generate a stroke count for each swim. Velocity data from the GPS was manually inspected for anomalies where an exclusion criteria was set for all strokes at $>1.94 \pm 0.05$ m s^{-1} for freestyle,[18] $>1.28 \pm 0.02$ m s^{-1} for breaststroke[5] and $>1.54 \pm 0.02$ m s^{-1} for butterfly.[5] Any values exceeding the exclusion criteria were discounted from further analysis.

Video footage from the trolley mounted camera was downloaded to analysis software (Connect Plus 5.5, Dartfish, Switzerland) to allow stroke counts of each effort to be determined. This process was performed by manual review of the footage by a single assessor who defined one stroke count as one hand entry (in the video camera view) to the next hand entry (or same hand re-entry in the case of freestyle). For breaststroke, each stroke was defined as end of the glide phase just prior to the catch to the next consecutive glide phase. Video footage from each of the tripod mounted cameras was downloaded into the GPS/accelerometer manufacturer supplied software (Logan Plus, version 4.7.1, Catapult Sports, Melbourne, Australia) where the participant's vertical jump landing was used to synchronise the video with the accelerometer data. To minimise video frame creep, the turn off the wall was used as a second synchronisation point as this was clearly discernible in both the accelerometer profiles and the video footage. The precision of the synchronisation process was well within the capture rate of the camera (25 Hz) as this process was only used to ensure the correct strokes recorded by the fixed video cameras were analysed and compared to the corresponding data from the GPS and the accelerometer. Once the corresponding sections of GPS velocity and video data were correctly identified, the GPS velocity was averaged to obtain a representative velocity of each mid-pool section while the video footage was manually digitised to obtain a criterion measure of velocity. This process was completed from the 0 to 10 m point of each mid-pool section using biomechanical analysis software (Hu-m-an Version 6.0, HMA Technology Inc., Canada). The bony landmark used digitisation in the butterfly and breaststroke trials was the nasal crest, while the most protuberant section of the occipital lobe, corresponding with the apex of the swimming cap was the chosen landmark in freestyle. This process allowed an average velocity to be calculated for each mid-pool section and this number was compared to the corresponding average mid-pool velocity measured by the GPS.

Test re-test reliability was conducted on the stroke count and velocity criterion measure. Stroke count identification and the manual digitisation process including the calibration process were repeated five times by a single investigator for five randomly selected participants across each stroke. Intra-class correlation coefficient (ICC) and percentage coefficient of variation (%CV)[19] were calculated for each test re-test reliability measure. The test re-test reliability of the criterion measure for stroke count (ICC = 1, %CV = 0) and velocity data including the calibration process (ICC ranging between 0.98 and 0.99, %CV of 0.07–0.11%), was found to be excellent in all three strokes.

The velocity data from GPS and criterion measure were normally distributed (Kolmogorov–Smirnov test, $p > .05$) and homoscedastic (non-significant Pearson's correlation between absolute residuals and predicted velocity measures[20]). Pearson's correlation coefficients were also calculated to examine the relationship between the video criterion measure of stroke count and the accelerometer derived measure. One-way analyses of variance (ANOVA), with device (GPS or criterion) as the within-participants factor were used to examine differences for butterfly, breaststroke and freestyle. The homoscedasticity and normality of each dataset required measurement error to be expressed in absolute terms. Accordingly, the 95% limits of agreement was calculated by $\pm 1.96\sqrt{2} \times \mathrm{MSE}$,[20] where MSE = mean square error obtained from the ANOVA. Similarly, the standard error of measurement (SEM) was defined as $\sqrt{\mathrm{MSE}}$.[21] The mean GPS velocity per stroke was expressed as a relative error to display the percentage variance where RE (%) = (SEM/measured value) × 100.[21] For both the 95% limits of agreement and SEM, 95% confidence intervals were calculated in Microsoft Excel. Statistical significance was set at $p < 0.05$.

3. Results

The number of visible satellites during the nine data collection sessions were 9 ± 1 (Trimble Navigation Limited, USA), with HDOP for freestyle, breaststroke and butterfly of 1.10 ± 0.18, 1.25 ± 0.30 and 1.53 ± 0.36, respectively. Initial assessment of the accelerometer traces revealed a distinct and clearly discernible pattern for breaststroke and butterfly. However, no clear pattern was observed for freestyle and as such, stroke count analysis was not performed on this stroke. High correlations (between 0.98 and 1.00) were observed for both the manual and automatic stroke count detection compared to the criterion measure stroke count for both breaststroke and butterfly.

Following adherence to the velocity data exclusion criteria previously outlined, swim velocity of 150 trials for freestyle, 148 for breaststroke and 134 for butterfly were analysed. No significant difference between the GPS velocity and the criterion measure was detected for both freestyle and breaststroke. There was however, a significant difference between the GPS velocity and the criterion measure for butterfly ($p < .001$). The SEM for freestyle, breaststroke and butterfly was 0.13 m s^{-1}, 0.12 m s^{-1} and 0.18 m s^{-1}, respectively. The 95% limits of agreement was 0.36 m s^{-1}, 0.33 m s^{-1} and 0.50 m s^{-1} with relative error measurements (%) ranging from 10.2 to 13.4% across the three strokes (Table 1).

4. Discussion

This study examined the criterion validity of integrated accelerometer and GPS technology to quantify stroke count and mid-pool velocity, respectively, in the three prone competitive swimming strokes. High correlations were observed for both the manual and automatic stroke count detection when compared to the criterion measure for breaststroke and butterfly while there was no significant difference between the GPS velocity and the criterion measure for both freestyle and breaststroke.

In the present study, the accelerometer integrated within the GPS unit proved to be a valid tool for stroke count quantification in breaststroke and butterfly ($r = 0.99$ and butterfly $r = 1.00$). Similarly, Ichikawa and associates[2] identified stroke count detection from an acceleration trace, using a set time phase to detect stroke entry and exit. Also, Le Sage et al.,[8] Thomas et al.[7] and Siirtola et al.[22] demonstrated accurate stroke recognition using automated stroke count detection for all four strokes. Thomas et al.[7] and Siirtola et al.[22] proposed a high accuracy model (<1% average error) used to automatically label and segment data for stroke count detection. Once again, these findings are in agreement with the current study's automated detection method of obtaining stroke counts. In the current study, freestyle stroke count was not discernible from the integrated acceleration profile. Other studies have been able to identify stroke counts in freestyle, with alternative accelerometer attachment sites at the wrist,[2] lower[7,8] and upper back.[22] The choice of the head placement in the present investigation was to optimise the GPS signal and although it limited the detection of

Table 1
Summary of GPS and criterion measure velocity data for freestyle ($n = 150$), breaststroke ($n = 148$) and butterfly ($n = 134$).

Stroke	GPS velocity (m s^{-1}) (95% CI)	Criterion velocity (m s^{-1}) (95% CI	SEM (m s^{-1}) (95% CI)	95% LOA (m s^{-1}) (95% CI)	Relative error (%)
Freestyle	1.28 ± 0.16 (1.25–1.32)	1.32 ± 0.14 (1.29–1.35)	0.13 (0.10–0.19)	0.36 (0.34–0.39)	10.2%
Breaststroke	0.94 ± 0.18 (0.90–0.98)	0.96 ± 0.09 (0.94–0.98)	0.12 (0.09–0.17)	0.33 (0.31–0.35)	12.8%
Butterfly	1.34 ± 0.25* (1.28–1.40)	1.19 ± 0.13 (1.16–1.22)	0.18 (0.14–0.27)	0.50 (0.47–0.54)	13.4%

Velocity values are means ± sd and (range).
* Significant main effect for device – GPS velocity different to criterion measure ($p \leq 0.05$).

stroke counts in freestyle, it did however optimise that of breaststroke and butterfly. The undulatory and cyclical mechanics of breaststroke and butterfly body position, and hence head position throughout the stroke cycle, creates a clear pattern to represent one stroke cycle[23,24] as clearly identified in the present study. Future work should focus on a placement for the device that optimises both the GPS and accelerometer signals for all the strokes in swimming.

The GPS unit used in this study was able to accurately quantify mid-pool velocity in freestyle (p = .103) and breaststroke (p = .221). In fact, the range of mid pool average velocities recorded by the GPS unit (Table 1) were similar to previously reported velocities measured by video analysis[5] and via tethered systems.[25] The GPS velocity displayed error measurements of 0.13 $m\,s^{-1}$ in freestyle and 0.12 $m\,s^{-1}$ in breaststroke when compared to the criterion measure. Similar error measurements have been shown when GPS was used to investigate linear gait analysis across a range of velocity values between 1.06 $m\,s^{-1}$ and 9.62 $m\,s^{-1}$,[14] and during linear cycling movements across speeds between 2.1 $m\,s^{-1}$ and 10.8 $m\,s^{-1}$.[12] Townshend and associates[14] identified 90.8% of the GPS velocity values fell within 0.10 $m\,s^{-1}$ of the criterion measure, while 97.9% were within 0.20 $m\,s^{-1}$. The similarities in these findings to the current study suggest the aquatic environment may not have had such a detrimental on the accuracy of the GPS.

The accuracy of the GPS during freestyle and breaststroke can be explained by the body position adopted by swimmers during these strokes. In freestyle, swimmers typically adopt a natural head position resulting in a near horizontal body position.[26] This exposes the most protuberant section of the occipital lobe and is more prominent in freestyle swimming. While momentary submersion of the unit may occur during freestyle breathing, it seemed to have minimal, if any effect on the error in recorded velocity. In modern breaststroke, the favourable high body position results in a head exposure for the majority of the stroke cycle, apart from the streamline or "gliding" phase.[23] In addition, low HDOP values (<2) indicate a relatively high quality and accurate satellite signal.[17] The HDOP in freestyle of 1.10 ± 0.18 and in breaststroke of 1.25 ± 0.30 fell within the acceptable limits of <2. Additionally, the average number of satellites employed by the GPS device in this study was 9 ± 1, in line with the acceptable 'line of sight' to greater than four satellites.[12] A clear 'line of sight' from the device to the satellites, exposes the GPS embedded antenna. This permits satellite lock and transmission of RF signals for velocity determination.[12]

In contrast, significant difference between the criterion measure of velocity and the GPS were detected during butterfly. The suggested technique for butterfly stipulates the vertical displacement of the head, trunk and shoulders exceed that of the hips,[24] with the head therefore positioned underneath the waterline for a large proportion of the movement. This technique suggests that the GPS device remained submerged for a large proportion of the stroke and as such, compromising the line of sight with the satellites. Future research should explore an alternative device placement that minimises the submersion of the GPS during butterfly.

5. Conclusion

GPS and accelerometer technology commonly used in field-team sport appears to provide an acceptable level of accuracy to quantify stroke count and mid-pool velocity in swimming. Findings from the current study show stroke count in breaststroke and butterfly but not in freestyle can be accurately detected from a head mounted accelerometer, while the GPS can validly quantify mid-pool velocity in freestyle and breaststroke. These positive results offer an innovative advancement in swimming kinematic analysis especially in the training environment where the integrated accelerometer and GPS device may provide an easy, objective and quick method for coaches and sports scientists to quantify stroke count and mid-pool swimming velocity. This is an important finding as the current method of obtaining both stroke count and velocity is limited to average measures from time consuming practices. Future studies should investigate the integration of wrist-placed accelerometers for freestyle stroke counts as well as an alternative unit placement for butterfly. Further, the method used in this study could also be extended to backstroke to enhance the utility of GPS technology across all four strokes in competitive swimming.

Practical implications

- Integrated GPS and accelerometer devices provide valid stroke count detection during breaststroke and butterfly, providing an attractive alternative to quantify stroke count data. Valid mid-pool swimming velocity in freestyle and breaststroke allow accurate velocity determination across distances of less than 25 or 50 m.
- The integrated GPS and accelerometer technology may not be a replacement for analysis conducted during competition as most major elite swimming meets are conducted indoors; however the system does offer the potential for swimmers, coaches and sports scientists to obtain kinematic measures of performance almost instantaneously in the outdoor training environment.

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