Approaching on-line estimation of swimming instantaneous velocity using a wearable IMU

Dadashi F. [1], Millet. G.P. [2], Aminian K. [1]
[1] Laboratory of Movement Analysis and Measurement, EPFL, Lausanne, Switzerland
[2] ISSUL Institute of Sport Sciences, UNIL, Lausanne, Switzerland

Abstract- The goal of this study is to assess the possibility of accurate on-line instantaneous velocity estimation in swimming. Having an on-line tool, coaches could provide immediate feedback about performance to trainees. More importantly, by on-line monitoring of velocity anomaly in open-water swimming, the safety of events can be significantly improved. We have previously introduced a method, using a wearable IMU, to estimate swimming instantaneous velocity, though information about pool length and a complete lap data were needed to correct the integration drift of IMU signals. In the present study, we used our previous algorithm for cycle's mean velocity estimation, as a criterion for drift correction in instantaneous velocity estimation without the knowledge about pool length. Using a simple within-cycle linear drift model, the relative error of the algorithm tested on 8 swimmers is 0.1±15.4%. As a result, the instantaneous velocity is available at the end of every cycle.

Keywords-performance; velocity; wearable sensor; swimming; drift correction

1. Introduction

Performance monitoring is a crucial task for elite athletes during both training and competition. Velocity is the key parameter of performance in swimming. Assessment of instantaneous swimming velocity has a twofold importance. First, it has been shown that intra-cycle velocity variation is a predictor of swimming energy expenditure [2]. Second, coaches can utilize the instantaneous velocity profile to design individually tailored allocation training i.e. how much time and distance should be dedicated to different actions in one swimming lap to optimize a swimmer's performance [3]. However, swimming performance evaluation remains immature due to the complexities of measurements in water [4]. The use of inertial measurement units (IMUs) in the aquatic environment turns out to be a viable option to study the swimming biomechanics [5, 6].

Using a single sacrum worn IMU in [1], we estimated the instantaneous velocity of front-crawl. We used a simple biomechanical constraint of front-crawl along with the change detection theory for piecewise modeling of velocity drift. This drift attenuation method induced an offset to the velocity profile. The velocity curve offset could be corrected in post-processing using the pool length. The method is accurate, though an on-line monitoring of instantaneous velocity cannot be carried out directly. In open-water swimming, athletes might require urgent medical care due to uncontrolled environmental conditions or adverse medical states. An on-line assessment of anomalies in the velocity pattern could immensely improve open-water swimming safety.

In the present work, we propose a solution for an on-line estimation of swimming instantaneous velocity using an IMU. We proposed to further developed the Gaussian process framework described in [7] to estimate the mean velocity at every swimming cycle, independent of knowing the pool length. We use the estimation of cycle's mean velocity to correct the instantaneous velocity drift for the corresponding cycle. We validated the accuracy of the proposed method through statistical analysis and comparison with a reference system.

2. Material and Methods

On-line Velocity Drift Correction Algorithm

The proposed velocity drift correction algorithm is carried out in two main steps at every cycle. First, we employ the estimation of orientation (using angular velocity data) to find acceleration and accordingly velocity in the global frame of study. This operation involves a drifted velocity pattern due to sensor inherent noises [1]. In the second step, using a linear drift model we correct the velocity profile as illustrated in Fig. 1 (a).

Suppose we have the average velocity of cycle k denoted by $\bar{v}_k$. Suppose also that the start and end times of the same cycle are given by t_{0_k} and t_{f_k} respectively. We show initial velocity of the cycle by v_{0_k} and assume that due to a linear drift pattern the cycle average velocity has been changed by a value of Δv_k as in (1):

$$\frac{1}{t_{f_k} - t_{0_k}} \int_{t_{0_k}}^{t_{f_k}} \left[\alpha\left(\tau - t_{0_k}\right) + v_{0_k}\right] d\tau = \Delta v_k \qquad (1)$$

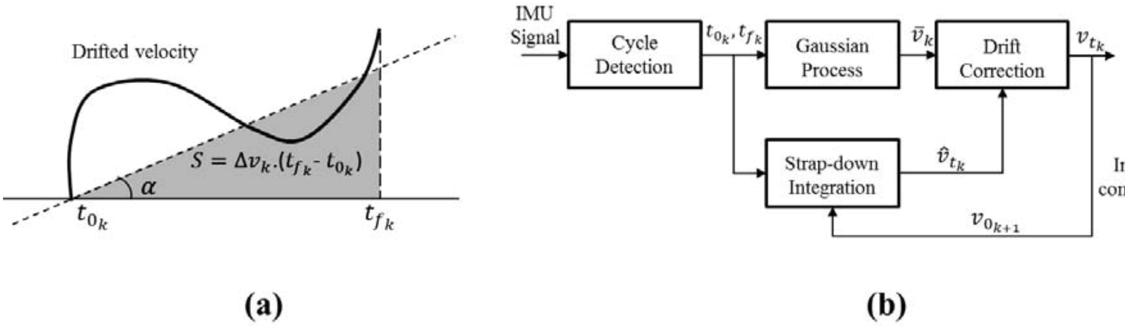

Figure 1. (a) Illustration of drift modeling based on value of error on cycle mean velocity, Δv_k. (b) Block diagram of the proposed on-line instantaneous velocity estimation algoritm.

Therefore, α, the slope of the linear drift can be calculated by (2):

$$\alpha = 2\frac{\Delta v_k - v_{0_k}}{t_{f_k} - t_{0_k}} \quad (2)$$

where the initial condition is $v_{0_1} = 0$, by starting the trials from a motionless period. In order to estimate the average velocity, $\bar{v}_k$, we used the method described in [7]. This consists extracting at every cycle, the relevant acceleration features and apply a Gaussian Process to estimate $\bar{v}_k$. Besides, as illustrated in Fig. 1(b), the drifted instantaneous velocity of the cycle, $\hat{v}_{t_k}$, has been estimated by applying the strap-down integration of kinematic signals. By applying the correction model (2) to $\hat{v}_{t_k}$, the instantaneous velocity, v_{t_k}, has been estimated. Finally, the initial condition for cycle *k+1* is determined as $v_{0_{k+1}} = v_{f_k}$.

Data Collection Protocol and Measurement System

Eight well-trained swimmers (2 female, 177.3±10.6 cm, 68.6±11.3 kg, 18.4±5.0 years) participated in the study. The experimental procedure was approved by the Ethics Committee of the Faculty of Biology and Medicine, University of Lausanne (protocol # 87/10) and followed the Declaration of Helsinki. Each swimmer performed four 25 m front-crawl trials consecutively from 70% to 100% of their personal maximum speed (considering their actual 100m record) by starting in water with a push off on the wall.

As the reference system, we used a tethered speedometer (SpeedRT®, ApLab, Italy, 100 Hz) that was attached to the waist of swimmers with a belt. A resistance of 5N was applied to keep the nylon line tight via a clutch on the pulley compartment of the apparatus. The swimmers were equipped with a waterproofed IMU (Physilog® III, GaitUP, Switzerland, 3D-accelerometer ±11 g, 3D gyroscope ±900 °/s, embedded data logger, 100 Hz). The IMU was worn on the sacrum inside the pocket of the swimming suit.

Statistical Analysis

We reported the total error of the algorithm as the RMS of difference between the estimated and reference instantaneous velocity curves over all trials of all participants. The RMS error was also calculated for each trial of the participants, separately. A Friedman test [8] (to consider the repeated measures) was used to investigate the existence of a significant difference in the RMS error medians for the four trials (significance level: $p<0.05$). Relative accuracy and precision at each trial have been assessed as the mean and standard deviation of instantaneous error normalized by the average velocity of the trial.

3. Results

Fig. 2(a) shows compares the instantaneous velocity of a swimmer obtained based on the proposed algorithm with the reference velocity over a single trial of 25 m. The RMS error of estimation is 19.2 cm/s corresponding to overall relative error of 0.1±15.4%. Fig. 2(b) represents the RMS estimation error for four trials. The Friedman test did not show any significant difference between median value of RMS error as a function of trials ($p>0.74$). Fig. 2(c) shows that except for subject 4, the relative error of trials is generally smaller than average relative error.

4. Discussion

The presented algorithm extends our earlier works in [1] and [7] to an on-line estimation of instantaneous velocity. The results show that a reliable on-line instantaneous velocity estimation is possible when the average estimation of cycle velocity (according to [7]) is used to rectify the drift of IMU strap-down operation.

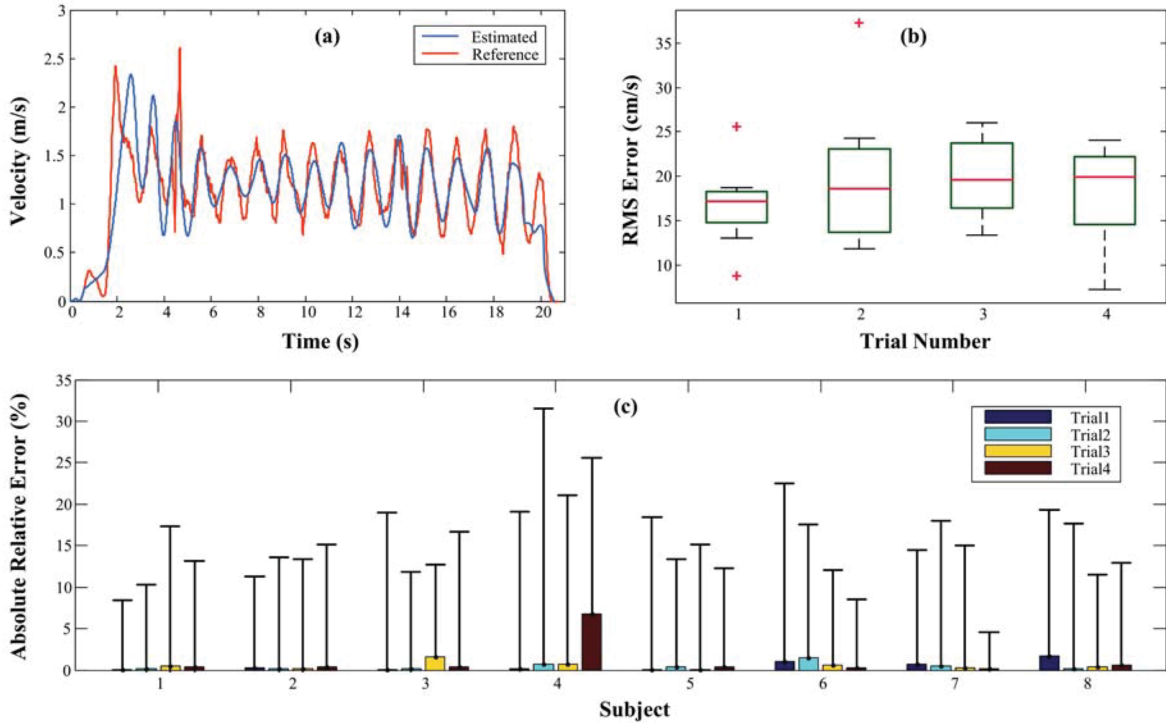

Figure 2. (a) An example of proposed on-line instantaneous velocity method vs reference system. (b) RMS error of estimation for all subjects at four trials. (c) Absolute relative error (absolute value of relative error mean plus relative error standard deviation) of estimation represented at four trials for every subject.

Nevertheless, the estimation error is larger than that of proposed in [1] (RMS error: 11.3 cm/s). Two sources for this difference can be considered. Firstly, the error of estimating mean velocity using Gaussian process regression [7] propagates to the slope estimation in (2). Secondly, an even more important error can originate from the assumption of linear drift during one cycle according to (1). As demonstrated in Fig. 2(a) the linear drift model cannot follow the changes of velocity, specifically in the beginning of the trial when a swimmer glides (with pushing off the pool's wall). A path to fix this problem is by identifying the family of functions (polynomial, hyperbolic, etc.) that best represents the difference between the drifted velocity (Fig. 1(a)) and the reference cycle velocity. Such a modeling approach could be realistic since strap-down integration of IMU is bounded by using the cycle mean velocity as a constraint.

The system allows coaches to individualize training program by observing minute details of performance at different intensities. On top of that, reviewing the USA Triathlon Fatality Incidents data from 2003 to 2011 period, shows that 30 out of 43 athlete fatalities, recorded during race events, occurred during the swim leg [9]. On-line monitoring of swimming velocity is thus required to reveal any anomalies in the swimmer's performance in order to improve open-water swimming safety.

5. Acknowledgment

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6. References

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