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REPRODUCIBILITY AND REPEATABILITY OF INTRACYCLIC VELOCITY VARIATION IN FRONT CRAWL SWIMMING FROM MANUAL AND SEMI-AUTOMATIC MEASUREMENT

original paper
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ABSTRACT
Purpose. Intracyclic velocity variation is an important kinematic parameter to evaluate swimming performance. It can be estimated by a fixed point at the swimmer's hip. The aim of the study was to determine the reproducibility and repeatability of active light markers to measure intracyclic velocity variation in swimming.
Methods. Reproducibility and repeatability were tested by image measurement, by five manual digitizing processes and five sessions of automatic tracking of a LED marker set in a swimmer's hip. The procedures were evaluated by the intraclass correlation coefficient, and the agreement between the methods was evaluated with Bland-Altman plots. The reproducibility was excellent in both procedures.
Results. The repeatability of manual digitalization ranged between satisfactory to excellent, while the repeatability of automatic tracking was excellent. In addition, the Bland-Altman plots displayed a good agreement between manual and automatic measurements. The automatic tracking was 27% faster than manual digitization.
Conclusions. Active markers are promising to evaluate the intracyclic velocity variation of swimmers, with a faster response than the common manual processing.
Key words: reproducibility, swimming, kinematic

Introduction

Kinematic analysis is a common method applied to assess swimming performance. Motion in swimmers is generally video-recorded and analysed by digitizing anatomical points [1].

A well-known kinematic parameter to evaluate swimming performance is the intracyclic velocity variation [2, 3], which indicates the acceleration and deceleration of a swimmer's body within a stroke cycle [3]. Considerable variations of the intracyclic velocity expose the swimmer to higher hydrodynamic forces, owing to high positive and/or negative body impulses, which may affect the energy cost [2] and swimming efficiency. The intracyclic velocity variation can be assessed either directly, by the reconstruction of a swimmer's centre of mass, or by a fixed point at the hip, which has been indicated as an easier and faster process than centre of mass calculation [3, 4]. In this context, two-dimensional kinematic analysis has been applied; because of the complexity of swimming environment, however, to evaluate the simultaneous displacement in three axes of a swimmer's body, a more realistic approach is required [5, 6].

Movement reconstruction by manual digitizing procedures depends on an operator identification, which may lead to misidentification of feature points and turn out time-consuming [1, 7]. Thus, the number of participants, trials, and stroke cycles to be digitized in a swimming analysis can be limited [8]. In addition, when a large set is required, the calibration area must be increased; consequently, the image to be digitized becomes smaller and body markers may also be harder to distinguish; as a result, accuracy may be reduced [8]. For instance, Olstad et al. [9] and Ribeiro et al. [10] applied automatic tracking with reflexive markers in a specific system developed for underwater analysis (Qualysis). However, the cost of the system is exceptionally high, and only a few laboratories in the world can afford such technology. In addition, Schreven et al. [11] used light-emitting diode (LED) markers to improve visualization, but maintained manual digitalization. Finally, Slawson et al. [12] applied light markers to allow automatic tracking at a low cost; nevertheless, the evaluations were again two-dimensional and could be utilized just for swimming starts and turns. To ensure reliable data analysis through automatic tracking measurement by light markers, re-

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producibility and repeatability of the measurements need to be tested. In this view, the aim of the study was to determine the reproducibility and repeatability of active LED markers of intracyclic velocity variation for the hip in swimming in a three-dimensional perspective. In addition, automatic tracking was compared with manual digitization, as well as the time spent to perform the measurements was assessed. High reproducibility and replicability of the methods were hypothesized, with less time spent to perform the semi-automatic tracking.

Material and methods

The 50-meter maximum swimming performance of one swimmer (age, 20 years; body height, 1.68 m; arm span, 1.80 m; body weight, 65 kg) was recorded by four underwater cameras (GoPro Hero 4) at 60 Hz, 1080 p resolution (1920 × 1080), in a previously calibrated volume (3.5 × 1.0 × 0.75 m for the X, Y and Z axes in the horizontal, vertical and lateral directions, respectively). The total of 45 control points were used for the Direct Linear Transform calibration. The cameras were set on the swimmer's body (two on the right and two on the left side), forming a rectangle. The cameras were synchronized by a light pulse. Reproducibility and repeatability were tested by repeating five manual digitizing processes and five sessions of automatic tracking of white LED markers set in the swimmer's swimsuit on the anterior superior iliac spine site (to represent the hip). The LED markers, characterized by a low cost, were fixed to a battery with waterproof glue. The three-dimensional kinematic measurement, of the right and left side of the swimmer (manual and automatic), was assessed with the SIMI Motion software (version 6.0). The time spent to reconstruct each image was measured. Velocity (in each coordinate) was calculated on the basis of the variation of the position as a function of time, frame by frame. No smoothing filter was applied for a realistic comparison of the variability between the reconstructions procedures.

Reproducibility and repeatability were established under the concept proposed by Taylor [13]. Reproducibility was defined as the closeness between the results of the same measurement carried out under different procedures (manual and automatic reconstruction). Repeatability was analysed by the proximity between the results of successive measurements carried out by the same procedure. The reproducibility and repeatability of the procedures were evaluated by the intraclass correlation coefficient (ICC). The coefficient values below 0.4 were interpreted as poor, between 0.4 and 0.75 as satisfactory, and above 0.75 as excellent. In addition, a standard measurement error and minimum detectable change of the resulting trajectory were evaluated between the methods. The agreement between the methods was evaluated with the use of Bland-Altman plots [14] with an XY scatter plot, in which the Y axis shows the difference between the paired two measurements (manual-automatic), and the X axis presents the average of those measures ([manual + automatic]/2). In other words, the difference between the measurements is plotted against the mean of the two measurements, and it was recommended that 95% of the data points should lie within the ± 2 *SD* of the mean difference [14]. Statistical analysis was performed with the Matlab 7.0 and the significance level adopted was $p < 0.01$.

Results

Manual adjustments were required owing to the automatic tracking system missing 13 (random) of 91 frames (i.e. the tracking was not totally automatic, but semi-automatic). This procedure spent approximately 13 minutes to reconstruct each marker vs. approximately 18 minutes taken by manual reconstruction. The reproducibility of the intracyclic velocity variation procedures was excellent for the three coordinate axes. The repeatability of manual digitalization ranged between satisfactory to excellent, while the repeatability of the semi-automatic tracking was excellent for all axes. The reproducibility and repeatability are presented in Table 1.

The standard measurement error of the resulting trajectory was approximately 1 mm, while the minimum detectable change equalled approximately 4 mm.

The Bland-Altman plots (Figure 1) displayed a good agreement between manual and semi-automatic measurements and were within the upper and lower threshold

Table 1. Reproducibility and repeatability for the right (R) and left (L) intracyclic velocity variation to the X, Y, and Z axes

Side	Axes	Reproducibility			Manual repeatability			Automatic repeatability		
		ICC	*F*	*p*	ICC	*F*	*p*	ICC	*F*	*p*
R	X	0.97	57.36	**< 0.01**	0.89	42.01	**< 0.01**	0.94	84.11	**< 0.01**
	Y	0.93	29.05	**< 0.01**	0.73	14.45	**< 0.01**	0.84	28.00	**< 0.01**
	Z	0.99	208.01	**< 0.01**	0.94	81.00	**< 0.01**	0.98	276.20	**< 0.01**
L	X	0.86	12.88	**< 0.01**	0.48	5.63	**< 0.01**	0.79	19.32	**< 0.01**
	Y	0.93	29.55	**< 0.01**	0.70	12.63	**< 0.01**	0.88	39.27	**< 0.01**
	Z	0.98	106.04	**< 0.01**	0.91	50.19	**< 0.01**	0.96	133.88	**< 0.01**

ICC – intraclass correlation coefficient

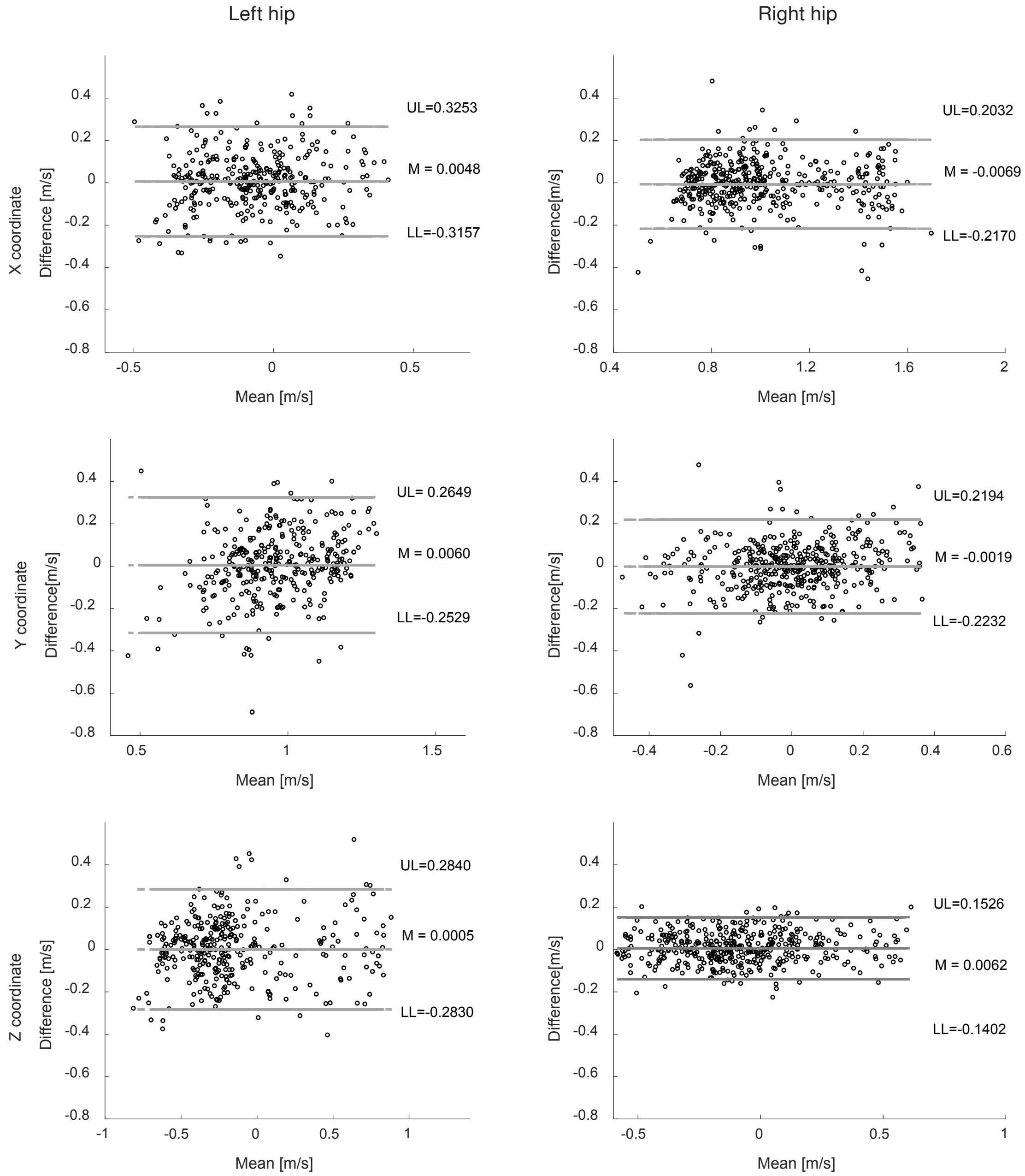

Figure 1. Difference between manual and automatic methods against the average of the measurement, bias, and limit of agreement. UL – upper limit, M – mean, LL – lower limit

limits of agreement. All mean differences between manual and semi-automatic measurements were not significantly different from zero. Thus, the range of bias for the measurement of the left and right hip (3 coordinates, i.e. the x, y, and z axes) was between –0.0069 and 0.0062 m/s. The biggest limits of agreement were –0.3157 and 0.3253 m/s for the X coordinate for the left hip, and the smallest limits were –0.1402 and 0.1526 m/s for the Z coordinate for the right hip.

Discussion

This study was designed to test the reproducibility and repeatability of light markers to analyse the intracyclic velocity variation in front crawl swimming. During semi-automatic tracking, approximately 14% of the frames required manual adjustments (when the marker was missed by the system). This result was lower than that found by Magalhaes et al. [7] with the same software (17%), although the authors reported less manual intervention with the software, which was developed by themselves for automatic tracking. This study utilized a commonly applied operational system for kinematic analysis [15–17]. In addition, despite the necessary adjustments, the semi-automatic tracking was 27% faster than manual digitalization (ca. 13 min for each marker reconstruction vs. 18 min for semi-automatic and manual procedures, respectively).

The high reproducibility and repeatability of semi-automatic tracking suggest a good applicability of the method. These results indicate a precise procedure that reduces processing time, which is in line with the observations by Slawson et al. [12], who did not find any significant difference between the angle of start and turn measured by manual digitalizing and automatic tracking. These findings are very crucial as kinematics requires extensive data processing (mainly in the 3D perspective), which delays the analysis. Thus, the use of an active marker can further improve the feedback for coaches and swimmers. In this view, an error of 1 mm in the trajectory is intrinsic to the measurement and only changes larger than 4 mm can be considered indicative of variability.

The Bland-Altman plot displayed a few outliers and provided differences between semi-automatic and manual measurements of 0.47 m/s. However, these results represent less than 5% of the total data sample. This implies that, although in most cases the differences observed through the Bland-Altman plots are small, the semi-automatic measurements are not interchangeable per definition. Therefore, filtering of the data and a visual control of the semi-automatic measurements are suggested.

Furthermore, limitations to the study have been acknowledged. Firstly, the small number of cameras did not allow for full markers visibility in all trajectories (a cycle stroke), which created a void of 10 frames (11% of the cycle). However, this issue occurs in both methods (manual and semi-automatic). For the purpose of the study, no procedure was applied to fill this gap, as interpolation or estimation could affect the realistic comparison between the measurement methods. In addition, the influence of the LED markers was not accounted for, which may have increased the passive drag.

Conclusion

To sum up, the reproducibility and repeatability in the semi-automatic tracking was very high, and there was an agreement with the manual method. Thus, active markers are very promising to evaluate the intra-cyclic velocity variation of swimmers in a wider scale, with a faster response than in the case of the common manual processing.

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