Engel A, Schaffert N, Wobbe JF, & Mattes K. Comparison of video and IMU data for analyzing the underwater dolphin kick.
J Sport Human Perf 2020; 8(1):1-11.
DOI: https://doi.org/10.12922/jshp.v8i1.165

JOURNAL OF SPORT AND HUMAN PERFORMANCE

ORIGINAL RESEARCH OPEN ACCESS

COMPARISON OF VIDEO AND IMU DATA FOR ANALYZING THE UNDERWATER DOLPHIN KICK

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ABSTRACT

Inertial Measurement Units (IMUs) increasingly gain scientific interest because they are less time-consuming and more cost-effective than traditional methods, i.e. video analysis to analyze performance-related parameters. Only few studies in swimming have addressed the underwater dolphin kick (UDK), known to have an important influence on overall swimming performance. The investigations of the UDK were limited to video analysis. Various factors were identified which have an impact on the UDK performance, such as the identical duration of up- and downbeat and constant frequency, resulting in a high toe speed and a large angular velocity of the hip.

The present study compares IMU data with video data of a kick cycle and the up and downbeat phase of the feet and hips. 11 national and international top athletes participated during regular diagnostic in the Olympic Training Center Hamburg. 110 Kick cycles were measured via video (50-100 Hz) and IMU (400 Hz, ± 16g, ± 2000°/s) and both measuring methods compared using the Bland-Altman Plot. The results of the hip-foot comparison within one method showed no significant difference, while the comparison of both methods showed a significant difference. We explain this by the inherent error in the detection of key positions from the video. From a practical viewpoint, the absolute difference (max. 0.07 s) is negligible. Future efforts is on software development, which automatically analyses the UDK and supports daily work from coaches and scientists.

Keywords: Swimming performance, Movement technique, Biomechanics, Inertial sensor, Bland-Altman Plot, Elite athletes

INTRODUCTION

In swimming, the use of inertial measurement units (IMU's) to analyze movement execution is becoming increasingly important (1, 2). The majority of the studies focus on the four competitive swimming strokes butterfly, backstroke, breaststroke and freestyle, while so far none addresses the underwater dolphin kick (UDK). This is astonishing, since Mason and colleagues (3, 4) could already show at the Olympic Games in 2000 that the execution of the UDK was one of the most important factors for the overall swimming performance.

The rules of the Fédération Internationale de Natation (FINA) allow athletes to swim a maximum of 15 meters under water after the start and each turn (5). This corresponds to 60% of the total distance in the short course pool (25 m length) and still 30% in the long course pool (50 m), which clearly shows the advantage of the swimmer who performs excellently in this underwater phase.

During the execution of the UDK, the swimmer is in a streamlined position and performs a whip-like motion with hip and feet. The oscillating motion starts at the trunk and a wave travels caudally to the toes and increases its amplitude at each body segment, transmitting an impulse from the larger body segments to the smaller parts (6-9). Thus, there is a down kick, which starts at the upper turning point (key position 1) and ends at the lower turning point (key position 2) of the feet and an upward kick vice versa (9-12). Note that the downbeat of the feet coincides with the upbeat of the hips and vice versa (Figure 1). Consequently, when analyzing the downbeat, the hip begins the movement at its lower turning point (key position 1) and ends at its upper turning point (key position 2). For the upbeat, it is the other way around.

The greatest propulsion is generated at the end of the downbeat and the swimmer decelerates during the upbeat (9, 13, 14). Research still focuses on video analysis as the gold standard, which is time-consuming and does not provide direct feedback to the swimmer (15).

The literature describes some requirements for an excellently executed UDK. Based on the study by Mason and colleagues (3, 4), other researchers investigated the requirements for a good UDK performance. Gavilán et al. (6) found, for example, that a high kick frequency has to be maintained to maximize speed. Shimojo and colleagues (16) and Yamakawa et al. (17) further emphasized that there is an individual best frequency for each athlete. If the athlete kicks below that frequency, the kick has a greater amplitude to increase the propulsion per cycle. In contrast, there is greater resistance at the turning points, which makes it impossible for the athlete to reach a high velocity. If, on the other hand, the athlete exceeds the personal “best” frequency, the kick amplitude narrows and the athlete can no longer generate as much propulsion as before.

Thirdly, Atkison and others (18) showed that the UDK must be performed symmetrical around the horizontal axis. In the study of 15 male athletes, the slower athletes spent more time in the upward motion than in the downward motion. The authors concluded that an effective UDK requires the same time for the upward motion as for the downward motion. These findings are confirmed by Yamakawa et al. (17). Further research by Higgs and colleagues (19) was consistent with the findings from Atkison et al. (18), showing that toe velocity and hip angular velocity are critical for a good performance.

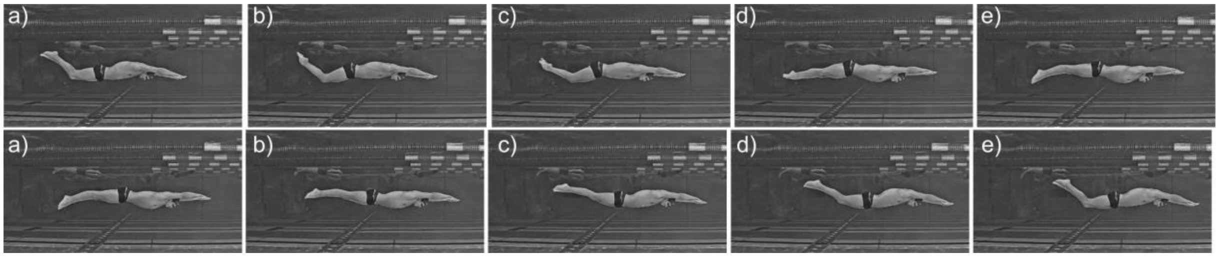

Figure 1. Upper row: Downbeat of the feet of an international top athlete. The movement begins when the feet reach the highest point of the cycle (a) and ends when the feet have reached the lowest point of the cycle (e). Note that the hip moves from the lowest point (a) to its highest point (e). Lower Row: Upbeat of the feet of an international top athlete. The kicking motion begins at the lowest point of the feet (a) and ends at the upper turning point (e). Note that the hip moves from its highest point (a) to the lowest point (e) of the cycle.

The aim of the study was to examine if performance relevant parameters (duration of one kick cycle, downbeat and upbeat for hip and feet respectively) of the UDK can be obtained from an IMU positioned at the lower back with the same or even higher accuracy compared to video analysis. Furthermore, it was examined if intra-cyclic parameters of the feet movement (duration of a kick cycle, downbeat and upbeat), which according to Higgs et al. (19) have proven to be performance relevant, can be determined from the hip-positioned IMU.

MATERIAL AND METHODS

Participants

Data of 11 national and international level athletes (5 males, 6 females, aged 20 ± 3.6 years) was taken during regular performance diagnostic at the Olympic Training Center Hamburg. Only athletes with no current or history of musculoskeletal or cardiovascular diseases or recent musculoskeletal injuries were considered. The participants gave their written consent to participate in the experimental procedure approved by the Institutional Ethics Committee. The study conformed to the provisions of the Declaration of Helsinki.

Procedure

Following the individual warm-up, each athlete completed one trial according to the standardized procedure of the regular training diagnostic. For the study, the athletes performed the UDK in a prone position with maximum intensity until the 15 m mark was reached.

Measuring systems

Video recordings were taken with four stationary underwater cameras positioned alongside the swimming pool with a sample frequency of 50-100 Hz, depending on the camera. The IMU data were collected with a sensor positioned on the lower back in a sewn pocket. The IMU contains a three-dimensional accelerometer (+/-16 g) and gyroscope (+/- 2000°/s) with a sample frequency of 400 Hz. The trials recorded on video were linked to the IMU data using the jBeam software (20), and the key positions of each cycle were related to the data.

Data processing

Based on current findings from Higgs and colleagues (19), the angular velocity of the hip (IMU_{Gyro-x}) and the forward acceleration (IMU_{Acc-y}) of the IMU was taken to determine the key positions. According to

Maglischo and others (9, 13, 14), forward acceleration is maximal at the end of the downbeat and minimal at the end of the upbeat. Both variables show a sinusoidal characteristic with sharp minima and maxima, so that the corresponding data points can be extracted with an error of ±1 samples, which corresponds to an error of 0.01 s.

The values for the duration of the downbeat as well as for the upbeat were extracted from the video for the key positions of the feet and hip, respectively, as shown in Table 1. Due to the sampling frequency of the video cameras and the uncertainty in detecting the key position of the athlete, there is an inherent error of 0.04 s in determining the phase duration from the video. The sum of the duration of the downbeat and upbeat resulted in a value for the entire kick cycle.

Statistical analysis

Selected parameters include the time duration for the downbeat (t_{DB}), upbeat (t_{UB}) and entire swimming cycle (t_{cycle}) were compared for (1) the hip movement from the video and the respective IMU data (IMU_{Gyro-x}), which measures the angular velocity of the hip around its transverse axis. An error of 0.05 s was estimated due to the sampling rate of the video; (2) t_{DB}, t_{UB} and t_{cycle} of the forward acceleration (IMU_{Acc-y}) data with the IMU_{Gyro-x} data. Here, an error of 0.01 s was estimated; (3) t_{DB}, t_{UB} and t_{cycle} of the movement of the feet from the video and the respective IMU data (IMU_{Acc-y}) with an estimated error of 0.05 s.

Statistical analysis included descriptive statistics (arithmetic mean and standard deviation) of the sample data. The Kolmogorov-Smirnov and Levene-Test was used to determine normal distribution and variance homogeneity.

Bland-Altman plots (21) were used to assess the agreement between the data from the two measurement systems, with the extracted video data serving as a reference for the sensor data of the respective channel (IMU_{Gyro-x} and IMU_{Acc-y}). Thus, the Bland-Altman plots show the difference in video data and the difference in IMU sensor data (y-axis) and the mean of the difference in video data and difference in IMU data (x-axis). The confidence interval (CI) was set to 0.95, i.e. about 95% of the points in the plots should lie within the limits; then the concordance between the two measurement methods is given. In addition, an ANOVA with repeated measures was performed to examine the significance between the measurements for the single movement phases (downbeat and upbeat) and the entire kick cycle. Statistical significance was at the $p<.05$ level. Partial eta-squared (η_p^2) was taken as effect size and determined as small (≥0.08), medium (≥0.20) and large (≥0.32) according to Cohen (22). A Pearson Correlation was performed to verify the relationship between the two measures. Statistical analysis was conducted using SPSS IBM 25.0.

Table 1. Key positions and related kick phases of the feet and hip.

	Downbeat				Upbeat			
	Feet	**IMU$_{Acc-y}$**	**Hip**	**IMU$_{Gyro-x}$**	**Feet**	**IMU$_{Acc-y}$**	**Hip**	**IMU$_{Gyro-x}$**
Starting position	Top turning point	Global minimum	Bottom turning point	Global maximum	Bottom turning point	Global maximum	Top turning point	Global minimum
End position	Bottom turning point	Global maximum	Top turning point	Global minimum	Top turning point	Global minimum	Bottom turning point	Global maximum

RESULTS

Hip data comparison (IMU$_{Gyro-x}$ vs. Video)

Figure 2 shows the Bland-Altman plots for comparing the data from the IMU$_{Gyro-x}$ and video for the downbeat (left graph), the upbeat (middle graph) and the entire kick cycle (right graph). The mean cycle time (t_{cycle}) determined from the video is 0.41 ± 0.04 s compared to the IMU measured time of 0.39 ± 0.04 s. That is a mean difference (bias) between the two systems of +0.01 s (95%-CI ranging from -0.05 to +0.08 s). The mean $t_{DBVideo}$ is 0.20 ± 0.03 s and mean t_{DBGyro} is 0.16 ± 0.04 s (bias of -0.05 s). Thus, the IMU underestimated the downbeat (95%-CI ranging from -0.03 to +0.13 s), whereas it overestimated the upbeat ($t_{UBVideo}$ = 0.20 ± 0.04 s and t_{UBGyro} = 0.24 ± 0.02 s) with +0.04 s (CI: -0.12 to 0.05 s).

The ANOVA analysis evidenced a significant difference between the two methods for the determined times of the complete kick cycle as well as for the downbeat and upbeat ($p < 0.01$ respectively) with high effect sizes (η_p^2) for the downbeat and upbeat. The results are reported in Table 2.

Foot data comparison (IMU$_{Acc-y}$ vs. Video)

Figure 3 shows the Bland-Altman plots for the video data of the foot movement compared to the forward acceleration from the IMU (IMU$_{Acc-y}$). When analyzing the complete kick cycle, there is only a small difference (bias) between the mean cycle duration extracted from video (t_{cycle} 0.40 ± 0.04 s) and forward acceleration of the IMU (t_{cycle} 0.40 ± 0.04 s) of +0.01 s (CI: -0.05 to +0.07 s).

The IMU underestimates the downbeat ($t_{DBVideo}$ 0.22 ± 0.02 s, $t_{DBAcc-y}$ 0.15 ± 0.06 s, bias = -0.07 s), with the 95%-CI ranging from -0.03 to +0.18 s, whereas the upbeat is overestimated ($t_{UBVideo}$ 0.18 ± 0.03 s, $t_{UBAcc-y}$ 0.25 ± 0.05 s, bias = +0.06 s; CI: -0.17 to +0.04 s). The ANOVA analysis showed again a significant difference between the two methods for the determined times of the complete kick cycle as well as for the downbeat and upbeat ($p > 0.05$ respectively), again with high effect sizes for the downbeat and upbeat, but small effect size for the complete cycle as shown in Table 2.

Comparison of IMU data for hip (IMU$_{Gyro-x}$) and foot (IMU$_{Acc-y}$) movement

Figure 4 shows the Bland-Altman plots for the comparison between the

IMU_{Gyro-x} and IMU_{Acc-y} data. Regarding the complete kick cycle, the bias of the mean values for t_{Gyro} (0.39 ± 0.04 s) and t_{Acc-y} (0.40 ± 0.04 s) is +0.00 s (CI: -0.03 to +0.03 s). The bias for the downbeat is -0.01 s ($t_{DBGyro-x}$: 0.16 ± 0.04 s, $t_{DBAcc-y}$: 0.15 ± 0.06 s) and for the upbeat +0.01 s ($t_{UBGyro-x}$: 0.24 ± 0.04 s, $t_{DBAcc-y}$: 0.25 ± 0.05 s) respectively. The 95%-CI ranging from -0.09 to +0.08 s for the downbeat and -0.07 to +0.09 s for the upbeat. In contrast, the ANOVA showed no significant difference between the hip- and feet movement neither for the complete kick cycle nor for the down- and upbeat ($p > 0.05$ respectively), again with high effect sizes for the downbeat and upbeat, but small effect size for the complete cycle (Table 3).

Table 2. Mean and standard deviation, bias, F-value, level of significance and effect size (η_p^2) for the comparison of the UDK cycle and the upbeat and downbeat determined with data from IMU_{Gyro-x} and IMU_{Acc-y} and video analysis.

Kick Phase	Mean ± SD [s]	Bias [s]	F-value	p-value	Effect size (η_p^2)	r-value
	Hip data comparison (IMU_{Gyro-x} vs. Video)					
Cycle	IMU_{Gyro-x} 0.39 ± 0.04 Video 0.41 ± 0.04	0.01	13.06	<0.01	0.11	0.67
Downbeat	IMU_{Gyro-x} 0.16 ± 0.04 Video 0.20 ± 0.03	0.05	157.32	<0.01	0.59	0.29
Upbeat	IMU_{Gyro-x} 0.24 ± 0.04 Video 0.20 ± 0.02	-0.04	105.53	<0.01	0.49	0.27
	Foot data comparison (IMU_{Acc-y} vs. Video)					
Cycle	IMU_{Acc-y} 0.40 ± 0.04 Video 0.40 ± 0.04	0.01	13.06	0.04	0.11	0.71
Downbeat	IMU_{Acc-y} 0.15 ± 0.06 Video 0.22 ± 0.02	0.07	157.32	<0.01	0.59	0.31
Upbeat	IMU_{Acc-y} 0.25 ± 0.05 Video 0.18 ± 0.03	-0.06	105.53	<0.01	0.49	0.12

Table 3. Mean and standard deviation, bias, F-value, level of significance and effect size (η_p^2) for the comparison of the UDK cycle and the upbeat and downbeat determined with data from IMU_{Gyro-x} and IMU_{Acc-y}.

Kick Phase	Mean ± SD [s]	Bias [s]	F-value	p-value	Effect size (η_p^2)	r-value
Cycle	IMU_{Gyro-x} 0.39 ± 0.04 IMU_{Acc-y} 0.40 ± 0.04	0.00	13.06	0.14	0.11	0.93
Downbeat	IMU_{Gyro-x} 0.16 ± 0.04 IMU_{Acc-y} 0.15 ± 0.06	-0.01	157.32	0.81	0.59	0.70
Upbeat	IMU_{Gyro-x} 0.24 ± 0.04 IMU_{Acc-y} 0.25 ± 0.05	0.01	105.53	0.13	0.49	0.62

ISSN: 2326-6333

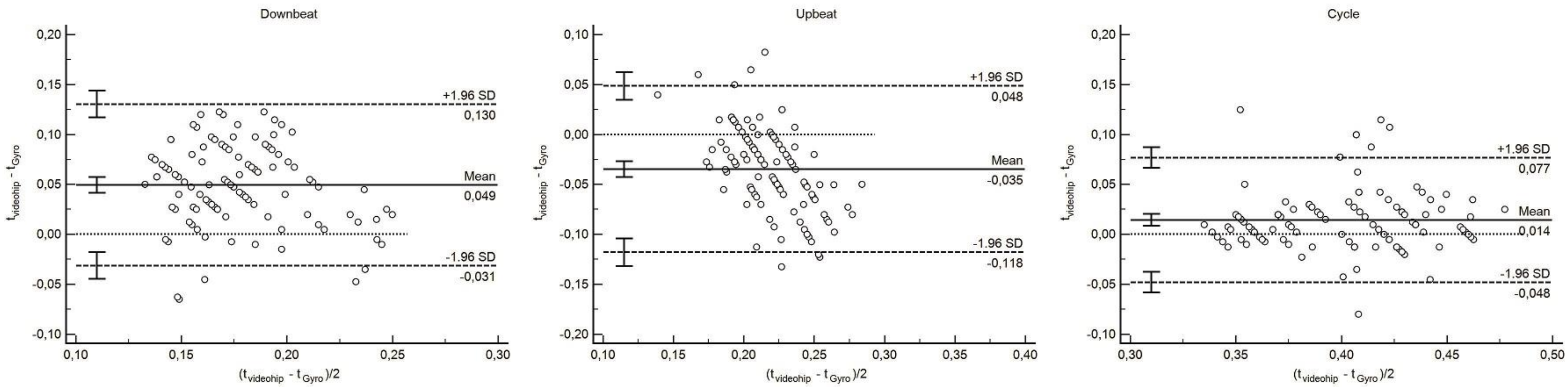

Figure 2. Bland-Altman-Plots for the comparison between the duration for each phase and the complete kick cycle for all 110 cycles with the IMU_{Gyro-x} data and video.

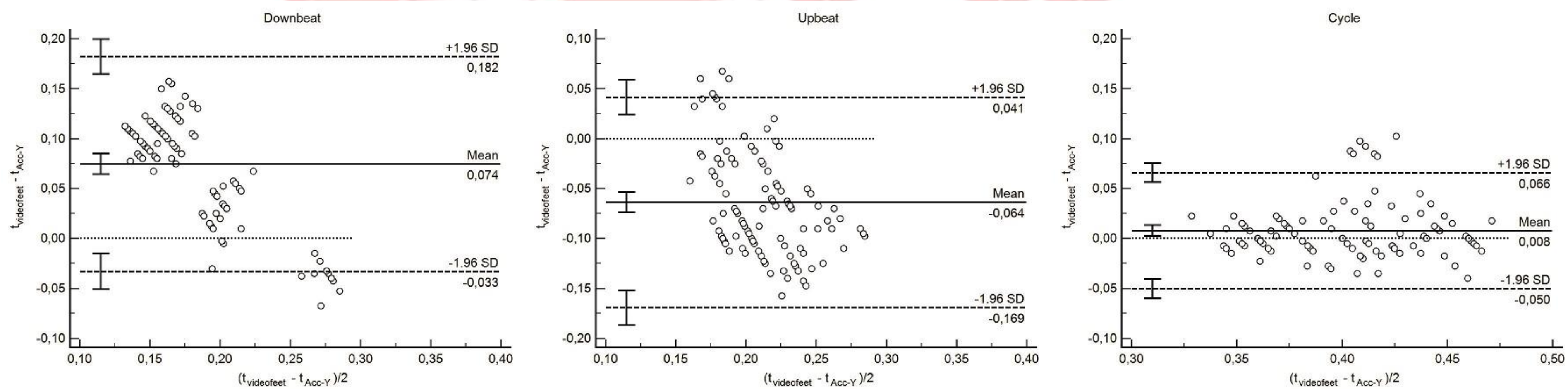

Figure 3. Bland-Altman-Plots for the comparison of the downbeat, upbeat and complete kick cycle with the IMU_{Acc-y} data and video.

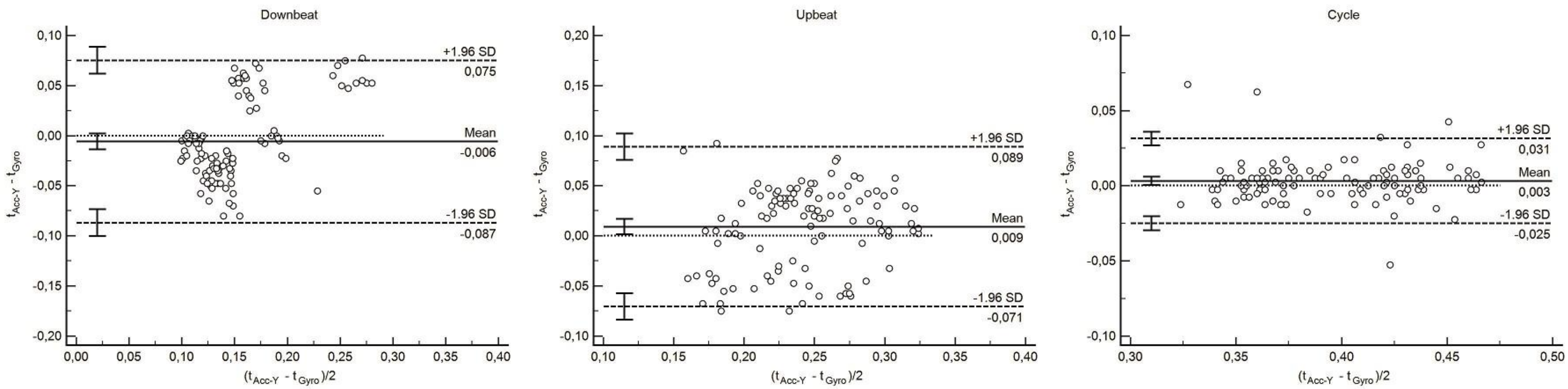

Figure 4. Bland-Altman-Plots for the comparison between the duration for each phase and the complete kick cycle for all 110 cycles with the IMU_{Acc-y} and IMU_{Gyro-x} data.

DISCUSSION

The study investigated whether there are differences in the measurement of performance relevant parameters of the UDK (duration of a complete kick cycle, downbeat and upbeat for hip and feet, respectively) between the data of an IMU positioned at the lower back of a swimmer and the data collected with the video.

When determining the upper and lower turning points of the hip or feet, a clear maximum or minimum could be observed in the IMU data, which was not comparably possible with the data from the video. In particular, no precise turning point for the hip could be determined from the video data. Because not every single kick cycle was performed perpendicular to the cameras, it was difficult to determine the key positions accurately and therefore estimate the durations for each phase. In addition, the lower sampling rate of the video (50-100 Hz) compared to the IMU data (400 Hz) increased the difference between the two methods, when finding the key positions.

This lead to a significant difference when estimating the durations of the downbeat, upbeat and the complete kick cycle. The IMU systematically underestimates the downbeat (hip: -0.05 s, feet: -0.07 s) and overestimates the upbeat (hip: 0.04 s, feet: 0.06 s) compared to the video. However, the differences from the IMU times almost compensated each other, so that the complete kick cycles differed in their mean times 0.01 s for both, hip and feet. Given an error of 0.01 - 0.02 s when detecting the key positions with video camera, these errors are of no practical relevance.

The duration of the particular kick phases determined from the video (downbeat: 0.20 ± 0.03 s, upbeat 0.20 ± 0.02 s) are similar to those reported from Higgs and colleagues (19) (downbeat: 0.20 ± 0.03 s, upbeat: 0.24 ± 0.06 s). The same applies to the comparison of mean times from the video for the complete cycle of our study (0.40 ± 0.04 s) with the times of Atkison and colleagues (0.47 ± 0.05 s) (18) and Gavilán et al. (0.45 s ± 0.03 s) (6). Thus, our data extracted from the video correlate with those from previous studies and provide appropriate values for a comparison with the IMU data. The duration extracted from the feet and hips for the complete kick cycle showed no significant difference ($p > 0.05$) for the comparison of forward acceleration (IMU_{Acc-y}) as an expression for the down- and upbeat of the feet with the angular velocity of the hip (IMU_{Gyro-x}), as shown in Table 2. This indicates that foot movement, which Higgs and colleagues (19) and Atkison et al. (18) have shown to be performance relevant, can be determined by a hip-positioned sensor.

Indeed, a significant difference was found for the comparison between the measurement systems (hip movement: $p < 0.01$; feet movement: $p = 0.04$; Table 3). This may be due to the inherent error in extracting the data from the video (due to the inaccurate key position detection). It is also assumed that the IMU data is more accurate and reliable. Finally, the absolute difference between the extracted values of each method is of no practical importance. When comparing hip movement, the maximum difference is 0.05 s, and when comparing foot movement, the maximum difference is 0.07 s. These differences are within the range of the estimated error of 0.05 s in the comparison of both methods (IMU vs. video) based on the sampling frequency of the four video cameras (50 and 100 Hz).

Limitations

Although this study demonstrated a promising approach for an automatic detection of performance-relevant parameters for the UDK, the limitations are that the data were only obtained with elite athletes. Thus, a transfer of the results to novice or regional athletes is not yet possible and should be investigated further. In addition, we recommend the use of a high-speed camera for future studies to minimize the error in the determination of the key positions of the athletes.

CONCLUSIONS AND PRACTICAL APPLICATIONS

The presented study compares for the first time video data and IMU data for the UDK for intra-cyclic (upbeat, downbeat) and inter-cyclic parameters (kick frequency). The results show, that it is possible to extract valuable and performance relevant characteristics for the UDK such as cycle duration, kick frequency, duration for downbeat and upbeat obtained with an IMU positioned at the lower back without the need for a professional video system.

Future work should focus on automatically analyzing the IMU data to provide direct feedback about the movement execution to coaches and athletes and to monitor performance improvements. The sinusoidal shape of the angular velocity of the hip as well as the forward acceleration makes these promising parameters for automatic analysis and at the same time provide valuable feedback to the user.

FUNDING

This research was funded by the German Federal Institute for Sports Science (BISp): ZMVI4-070804/19-21.

Acknowledgement

We would like to thank the team from the Olympic Training Center Hamburg and the participating athletes.

Conflict of interest declaration

The authors have no conflict of interests.

REFERENCES

1. Mooney R, Corley G, Godfrey A. Inertial sensor technology for elite swimming performance analysis: A systematic review. Sensors 2015; 16(1):18.
2. Magalhaes FAD, Vannozzi G, Gatta G. Wearable inertial sensors in swimming motion analysis: a systematic review. Journal of Sports Sciences 2015; 33(7):732-745.
3. Cossor J, Mason B. Swim start performances at the Sydney 2000 Olympic Games. ISBS-Conference Proceedings Archive (ed. RH Sanders), San Francisco, USA, 2001; 70-74.
4. Cossor J, Mason B. Swim turn performances at the Sydney 2000 Olympic Games. ISBS-Conference Proceedings Archive (ed. RH Sanders), San Francisco, USA, 2001; 65-69.
5. FINA, http://www.fina.org/sites/default/files/2017_2021_swimming_16032018.pdf (last time accessed: 22 January 2020).
6. Gavilán A, Arellano R, Sanders R. Underwater undulatory swimming: Study of frequency, amplitude and phase characteristics of the 'body wave'. Biomechanics and Medicine in Swimming X 2006; 35-37.
7. Sanders RH, Cappaert JM, Devlin Wave characteristics of butterfly swimming. Journal of Biomechanics 1995; 28(1):9-16.
8. Ungerechts BE. A comparison of the movements of the rear parts of dolphins and butterfly swimmers. Biomechanics and Medicine in Swimming 1983; 215-221.

9. Maglischo EW. Swimming even faster. McGraw-Hill Humanities: Social Sciences & World Languages; 1993.
10. Schramm E. Sportschwimmen: [Hochschullehrbuch]. Sportverlag; 1987.
11. Counsilman, JE, Counsilman BE. The new science of swimming. Benjamin-Cummings Publishing Company; 1994.
12. Madsen Ö, Reischle K, Rudolph K. Wege zum Topschwimmer Band 1 -3. Hofmann; 2014.
13. Arellano R, Pardillo S, Gavilán A. Underwater undulatory swimming: Kinematic characteristics, vortex generation and application during the start, turn and swimming strokes. In Proceedings of the XXth international symposium on biomechanics in sports 2002; 29-41.
14. Ungerechts B, Persyn U, Colman V. Analysis of swimming techniques using vortex traces. In ISBS-conference proceedings archive. 2000
15. Callaway AJ, Cobb JE, Jones I. A comparison of video and accelerometer based approaches applied to performance monitoring in swimming. International Journal of Sports Science & Coaching 2009; 4(1):139-153.
16. Shimojo H, Sengoku Y, Miyoshi T, Tsubakimoto S, Takagi H. Effect of imposing changes in kick frequency on kinematics during undulatory underwater swimming at maximal effort in male swimmers. Human Movement Science 2014; 38:94-105.
17. Yamakawa KK, Shimojo H, Takagi H, Tsubakimoto S, Sengoku Y. Effect of increased kick frequency on propelling efficiency and muscular co-activation during underwater dolphin kick. Human Movement Science 2017; 54:276-286.
18. Atkison RR, Dickey JP, Dragunas A. Importance of sagittal kick symmetry for underwater dolphin kick performance. Human Movement Science 2014; 33:298-311.
19. Higgs AJ, Pease DL, Sanders RH. Relationships between kinematics and undulatory underwater swimming performance. Journal of Sports Sciences 2017; 35(10):995-1003.
20. jBeam, https://www.amsonline.de/de/produkte/jbeam/ (last time accessed: 22 January 2020).
21. Bland JM, Altman DG. Measuring agreement in method comparison studies. Statistical Methods in Medical Research 1999; 8(2):135-160.
22. Cohen J, A power primer. Psychological Bulletin 1992; 112(1):155.