IMU-based Pose Determination of Scuba Divers' Bodies and Shanks

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***Abstract*—A simple method for an underwater pose determination of scuba divers can provide a deeper insight in the biomechanics of scuba diving and thereby improve education and training systems. In this work, we present an inertial sensor-based approach for the pose determination of the upper body and the shank orientation during fin kicks. Accelerometer measurements of gravity and a gyroscope-based method are used to determine absolute body angles in reference to the ground and the angular change of the shanks during fin kicks. The proposed algorithms were evaluated with data acquired from ten divers and a camera-based gold standard. The results were analyzed to a mean error of 0° with a standard deviation of 10° for the upper body pose determination. The absolute angle of the shanks at the turning points between fin kicks was determined with an error of $0^\circ \pm 11^\circ$, the relative shank angle with an error of $0^\circ \pm 8^\circ$.**

I. Introduction

A reliable determination of a diver's pose during underwater swimming is a key part for biomechanics research and its application to advanced training methods. Based on a combination of several body segment angles during a defined motion period (e.g. one fin kick), a biomechanical model can be derived to characterize the movement of a diver. This movement can then be described and compared to other divers. Furthermore, the established movement can be applied to simulations in order to obtain the influence of different swim styles and different dive scenarios (e.g. drift dive, deep dive). Thereby, new training methods for divers could be established. In addition to establishing a biomechanical model, pose determination methods can enhance scuba diving education and training systems. Divers could monitor their underwater motion in real-time or obtain a feedback of their performance based on already existing or newly developed training methods.

State of the art algorithms for in-use orientation determination in sports are often based on inertial measurement units (IMU) [1]. Thereby, accelerometer, gyroscope and further sensor measurements are combined in order to compute the current pose of an athlete. The advantage of IMUs in contrast to e.g. camera-based data recordings lies in the wide range and easy application in unsupervised scenarios. In scuba diving, an IMU-based measurement can be applied in the open sea or in deep dives where a camera surveillance is not feasible anymore.

Approaches for an IMU-based orientation determination in sports were applied in various projects. Groh et al. [2] proposed a jump angle determination in ski jumping and Jakob et al. [3] estimated the knee angle of athletes during dynamic motions. Projects considering water-based scenarios mainly focused on the evaluation of swimming techniques and styles. Bachlin and Tröster [4] evaluated the technique and performance of swimmers based on accelerometers. Jensen et al. [5] and Dadashi et al. [6] applied IMU-based methods for the classification and phase detection in swimming. One approach to apply IMU-based algorithms to scuba diving was proposed by Kuch et al. [7]. They used IMU-measurements for the determination of the diver's body orientation in order to create a localization framework. However, their approach did not analyze the diver's motion in respect to the establishment of a biomechanical model. Studies in the field of underwater biomechanics and training systems were only performed by video-based methods. Samimy et al. [8] proposed a video analysis of fin swimming, followed by an optimization approach of Wylegala et al. [9]. Steinberg et al. [10] developed a video-based training system to determine the performance of fin swimmers considering swimming technique and equipment configuration.

None of the aforementioned projects considered the application of IMU-based pose determination to an underwater scenario in order to obtain motion information about the biomechanics of scuba diving. In this work, we propose an inertial sensor-based orientation determination for the application in scuba diving. The upper body pose in non-motion states as well as the shank orientation during fin kicks is calculated in order to create a foundation for the establishment of a biomechanical model and to support the scuba diving training.

II. Methods

A. Data acquisition

1) Sensor hardware: The data acquisition was based on the miPod sensor system [11]. The miPod hardware contained an inertial measurement unit with a three-axes accelerometer and a three-axes gyroscope. The IMU was configured to an accelerometer range of $\pm 4\,$g, a gyroscope range of $\pm 1000\,^\circ$/s and a sampling rate of 200 Hz with a 16-bit resolution per axis. Three IMU devices were attached to each diver: one to the chest and two to the shanks. The sensors were placed into a waterproof mobile bag and two underwater camera housings and fixed with straps. Fig. 1 shows the attachment of all sensors.

The conducted study partially required a stationary position of the diver in the pool. Therefore, a fixed and stable construction that the subjects could hold on to was needed. In addition, it had to be aligned parallel to the ground of the pool and had to be wide enough for the diver to lie on. A wooden bench was chosen and placed into the pool. The bench was pinned to the ground by attaching additional weight of 30 kg.

For the evaluation of the IMU-based orientation determination, a video recording was chosen. Therefore, an underwater camera Sealife DC1400 HD with a frame rate of 30 fps and a resolution of 1280 x 720 pixels was used. It was built up stationary on a tripod so that the image plane represented the sagittal plane of the diver and thereby included the roll axis of the bench in a distance of approximately 5 m (Fig. 2).

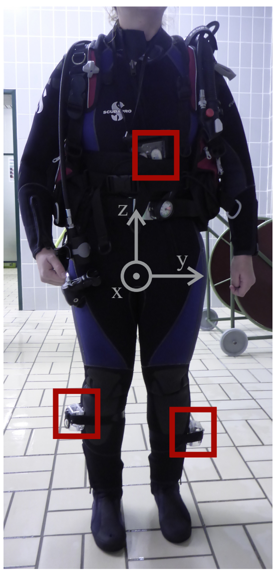

Fig. 1. Attachment of the inertial sensors to the diver's body. One IMU was mounted to the chest in an underwater mobile bag and fixed with straps. One further IMU was attached to each shank in a waterproof camera housing.

2) *Study design:* Ten licensed and experienced scuba divers (6 female, 4 male, age [years]: 37 ± 9, height [cm]: 172 ± 9) participated in the study. They had to perform predefined motion and non-motion scenarios. All scenarios were documented in a detailed study protocol for later evaluation. The subjects were informed of diving-related risks and gave written consent to participate in the study and for the collected data to be published.

The preparation part of the data collection consisted of defined resting positions of the diver outside the pool in order to calibrate for misalignments of the sensors. Therefore, the subject had to stand still and lie face-down on the ground for approximately 15 s. The main part of the data collection was separated into two aspects: the determination of the upper body orientation and the determination of the shank orientation.

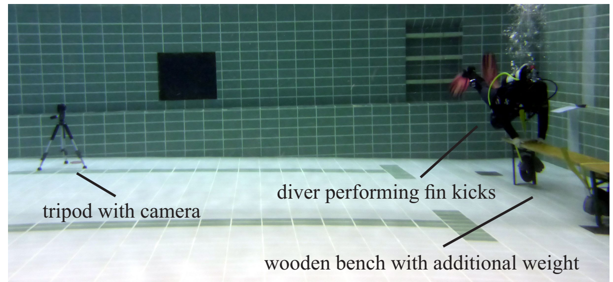

Fig. 2. The image of the underwater scenario shows the diver performing fin kicks on the wooden bench. The camera was positioned with a distance to the diver of approximately 5 m.

The upper body orientation was obtained by processing the measurements of the IMU at the chest. Each subject had to rest in four to eight different poses for 10 s each. These poses should include inclination of the diver's frontal plane to represent different upper body angles in reference to the ground. An example of three non-motion positions is shown in Fig. 3.

For the shank orientation determination, the diver had to lie face-down on the bench, covering the bench up to the hip. The legs were supposed to not to touch the bench in order to perform a fin kick motion with regular kicks (flutter kicks). Three fin kick intervals were requested: a slow motion interval with low amplitude, a strong motion with high amplitude and a self-defined pattern that represented the fin kicks of a typical dive. Approximately twenty kicks were requested per interval with a break of 15 s in-between the intervals. One kick was defined by a half motion cycle of the typical up-and-down movement. For instance, one kick was performed by changing from [left leg up - right leg down] to [left leg down - right leg up].

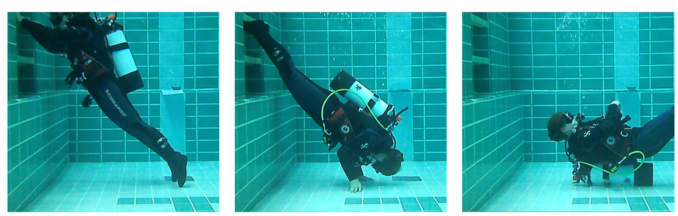

Fig. 3. Three examples of the diver's non-motion poses in order to evaluate the orientation determination algorithm with the IMU attached to the chest.

B. *IMU calibration and misalignment correction*

The exact computation of the collected data required an initial inertial sensor calibration. Therefore, the sensors were calibrated two hours before the data collection by following the calibration approach of Ferraris et al. [12].

Furthermore, a misalignment correction was performed separately for each subject. Two coordinate systems were defined: the body frame $\boldsymbol{C}_b$ and the sensor frame $\boldsymbol{C}_s$. The body frame was defined to represent the axes of the diver's body by the sagittal axis x, the frontal axis y and the longitudinal axis z (Fig. 1). The sensor data were obtained in the sensor frame which due to slightly varying sensor attachment did not completely match with the body frame. Therefore, the acceleration measurements of the static positions standing and lying face-down were obtained, averaged over the resting intervals and normalized to the static acceleration measurement vectors $\hat{\boldsymbol{a}}_{s,standing}$ and $\hat{\boldsymbol{a}}_{s,lying}$. The expected measurement in the body frame were defined to $\boldsymbol{a}_{b,standing} = [0, 0, 1]^T$ and lying face-down $\boldsymbol{a}_{b,lying} = [-1, 0, 0]^T$. Based on an adopted version of the algorithm of Kabsch [13] that did not allow translation of the system, the two vector pairs were used to create a rotation matrix $\boldsymbol{R}_s^b$ that rotated $\boldsymbol{C}_s$ to $\boldsymbol{C}_b$. The rotation matrix was applied to all subsequent sensor measurements.

C. Upper body orientation in non-motion periods

The pose of the upper body was determined based on the distribution of gravity on the three accelerometer axes. In non-motion periods, the measured acceleration ideally only represented the gravity. The measurements of each period were averaged to the acceleration vector $\boldsymbol{a}$. Assuming the diver lying face-down in the water while diving, the pitch angle θ was defined by a rotation about the y-axis. The angle could thereby be calculated by processing the x- and z-components of the acceleration measurement $\boldsymbol{a}$ with

$$\theta = arctan\left(\frac{a_z}{a_x}\right). \tag{1}$$

The roll angle (rotation about z-axis) could be calculated by the y- and z-components, respectively, but was not evaluated in this work.

D. Shank orientation

1) Automatic kick detection: The shank orientation determination during the fin kick performance was applied to the data of the three fin kick intervals per subject. Before the calculation of each single kick could be performed, the signal of each interval had to be separated into the time intervals of the single kicks. Therefore, an automatic kick detection algorithm was established using the gyroscope data. The start and end of a kick was defined at the turning point of the up-and-down rotation. Hence, one kick was either the movement from the highest to the lowest or from the lowest to the highest position of the sensor attached to the shank. Left and right leg were analyzed independently.

The first step towards automatic kick detection was based on Dynamic Time Warping (Berndt and Clifford [14]) in order to recognize a defined motion pattern. The template-based algorithm was extended to Subsequent Dynamic Time Warping (subDTW) following the approach of Müller [15]. Thereby, a defined fin kick template could continuously be detected in the inertial sensor signal independently of the motion pace. Due to the main rotation about the y-axis, only the y-axis of the gyroscope signal was processed by the algorithm. The template was created only once by selecting one random fin kick of the first subject. Due to a more stable subDTW performance, the start and end point of the template was not defined as the start and end point of the kick but as the local minima of the gyroscope signal (Fig. 4).

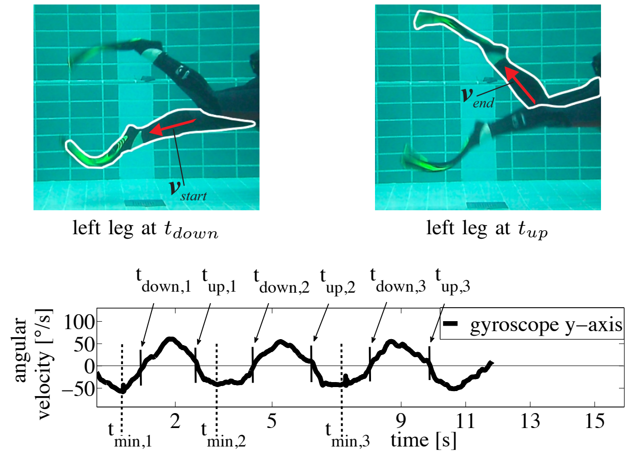

Fig. 4. Camera screenshot at two subsequent turning points of the left leg and example gyroscope signal (y-axis) of three fin kicks. The turning points between the up-and-down rotations t_{down} and t_{up} are visualized in the camera screenshot and marked at the corresponding time steps in the signal. In contrast, a subDTW detected kick was defined between the signal's local minima t_{min}.

In a second step, the actual turning points of the up-and-down rotation (at t_{down} and t_{up} in Fig. 4) were computed based on the previous subDTW detection. Therefore, the time steps of the zero-crossings of the y-axis gyroscope signal were determined. Fig. 5 shows the y-axis gyroscope signal of one fin kick interval and the two step-approach of first separating the signal with subDTW and then detecting the required turning points.

2) Accelerometer-based absolute shank angle: Two different methods were applied to determine a representative shank angle. The first method was based on the accelerometer measurement. Similar to the upper body angle calculation, the aim was to determine the orientation based on the gravity distribution on the accelerometer axes. Hence, the resulting angle is referred to as *absolute angle*. It was assumed that the measurements at the turning points between the up-and-down

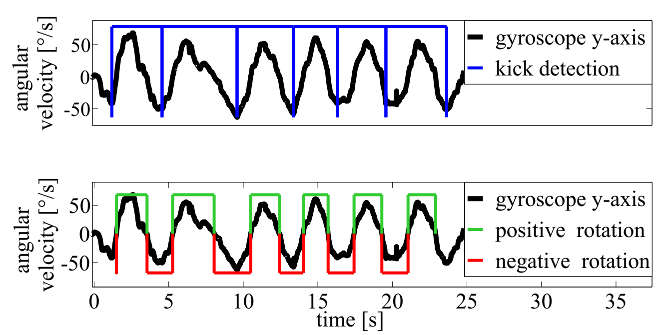

Fig. 5. Two stage approach to determine the turning point of the up-and-down movement. The subDTW algorithm separated the signal based on the local minima (upper plot). The zero-crossings defined the actual turning point before and after each kick (lower plot).

movement did not contain any motion-based acceleration but only gravity. Hence, (1) was applied in all turning point positions.

3) Gyroscope-based relative shank angle: In the second method for obtaining a representative shank angle, the gyroscope data were processed. The goal was to calculate the relative angle between each start and end of one kick (hence: *relative angle*). Therefore, two vectors $\boldsymbol{v}_{start}$ and $\boldsymbol{v}_{end}$ were defined. $\boldsymbol{v}_{start}$ was supposed to represent the shank at the beginning of a kick, $\boldsymbol{v}_{end}$ at the end (Fig. 4). The relative angle was calculated as the angle between both vectors. For matters of simplicity, $\boldsymbol{v}_{start}$ was defined to

$$\boldsymbol{v}_{start} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

in each calculation. $\boldsymbol{v}_{end}$ was obtained by rotating $\boldsymbol{v}_{start}$ with the rotation matrix $\boldsymbol{Q}_{start}^{end}$ as in (3). The rotation was established by computing the three-axes gyroscope measurements by quaternion-based calculation methods (Kuipers [16]). A quaternion-based calculation was chosen in order to avoid possible inaccuracies of simply integrating the gyroscope output of the single axes.

$$\boldsymbol{v}_{end} = \boldsymbol{Q}_{start}^{end} \cdot \boldsymbol{v}_{start} \tag{3}$$

In order to enable a two-dimensional camera-based evaluation, the relative angle between both vectors was required from the camera's perspective, hence, in the sagittal plane of the diver. Therefore, $\boldsymbol{v}_{end}$ was projected to the x-z-plane. With the definition of $\boldsymbol{v}_{start}$ of (2), the required relative angle θ_{rel} was calculated by the x- and z-components of $\boldsymbol{v}_{end}$.

$$\theta_{rel} = arctan\left(\frac{v_{end,z}}{v_{end,x}}\right) \tag{4}$$

E. Evaluation

1) Upper body orientation: For the evaluation of the upper body angle, the accelerometer signal intervals of the non-motion poses were processed. The length of the signal intervals varied between 0.5 s and 8 s depending on the ability of the diver to keep a stable position. The intervals were selected manually based on the study protocol, the video recording and the acceleration signal. Some intervals were excluded from the evaluation as there was no stable position distinguishable. In total, 33 poses were analyzed. The result of the proposed angular calculation was compared to the camera-based orientation determination. Therefore, one video frame per pose was selected and processed manually with *Kinovea* [17] software. *Kinovea* provided an angle determination based on two manually defined vectors. The evaluation of the example images of Fig. 3 is visualized in Fig. 6.

2) Shank orientation: In a first step, the performance of the algorithm to separate fin kick intervals into single fin kicks was evaluated. Therefore, fin kick intervals were selected manually from the gyroscope signal. Some intervals had to be excluded from the evaluation as the subjects did not perform the required typical up-and-down fin kick motion of flutter kicks. In total, the selected intervals contained 630 fin kicks. Due to the separate processing of the signals of the left and right leg, a total number of 1260 kicks were analyzed by the kick detection algorithm. The evaluation criterion for the successful detection of a kick was a defined accuracy of detecting the requested turning points. All results within the distance of 5 samples (0.025 ms) to the manually determined turning points were rated as correct.
In the second step, the shank angles were calculated for correctly identified turning points. For the absolute angle determination, the instances at the obtained turning points were evaluated. For the relative angle determination, the processed motion data of all time steps between turning points were evaluated. The results of both methods were compared to the video recording-based analysis of *Kinovea*.

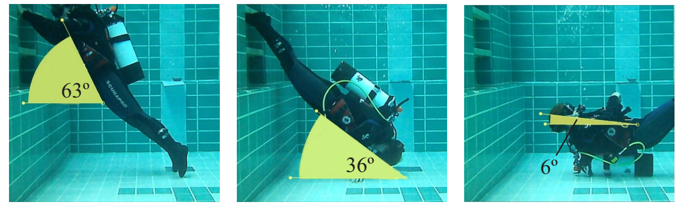

Fig. 6. Evaluation of the upper body orientation with *Kinovea* software. The angle in reference to the ground is visualized for three different example poses.

TABLE I
RESULTS OF THE SHANK ANGLE DETERMINATION ANALYSIS PERFORMING FIN KICKS. THE RESULTS SHOW THE MEAN ERROR AND THE STANDARD DEVIATION OF THE COMPARISON TO THE CAMERA-BASED REFERENCE.

	absolute angle [°] mean ± SD		**relative angle [°]** mean ± SD	
	left	**right**	**left**	**right**
low kicks	1 ± 8	0 ± 8	1 ± 5	1 ± 8
high kicks	-2 ± 10	-1 ± 17	0 ± 9	-1 ± 13
self-defined kicks	-1 ± 8	1 ± 11	1 ± 5	0 ± 5
	-1 ± 9	**0 ± 13**	**0 ± 7**	**0 ± 9**
	0 ± 11		**0 ± 8**	

III. RESULTS

The upper body angle determination in the non-motion poses resulted in a mean error of 0 ° with a standard deviation of 11 °. The fin kick detection algorithm identified 1063 of the 1260 kicks which equals a sensitivity of 84.4 %. There was no false positive match in the evaluation. The results of the fin kick angle accuracy in Tab. I are distinguished between left and right leg with low, high and self-defined kicks and provide the relative and absolute angle determination. The evaluation showed an overall error of $0° \pm 11°$ for the accelerometer-based absolute and $0° \pm 8°$ for the gyroscope-based relative kick angle.

IV. Discussion

The evaluation showed that an angular determination of the upper body pose in non-motion states is possible in the error range of $0^\circ \pm 11^\circ$. Assuming a low acceleration of typical dives, a pose determination of the upper body would also be feasible in movement periods. Therefore, the error influence and possible accuracy still has to be analyzed. In addition, despite calculating the inclination angle about the frontal plane (pitch angle), this study did not evaluate the three-dimensional orientation of the diver. It can be assumed that further angles can be determined with a similar accuracy but for the final application of a three-dimensional underwater orientation system, further analyses are necessary.

The results showed that the automatic fin kick detection algorithm could successfully be applied. However, a pre-selection of fin kick intervals was necessary. The development of a real-time system would require the capability of detecting fin kicks during the whole dive. Furthermore, only regular kicks (flutter kicks) were detected and evaluated. Experienced divers often use further kicks (e.g. frog kicks) that were not considered in this work.

The evaluation of all angle determinations (upper body, absolute and relative shank) showed an overall average error of $0^\circ \pm 10^\circ$. The zero-mean shows that there is no systematic error in the measurement. However, the system contains inaccuracies which are reflected in the standard deviation. These can partially be explained by the manually performed two-dimensional video validation. Although the camera recorded in high resolution, a video-based angle determination combined with a manual analysis of the angle has its limitations in terms of perspective-related, resolution-related and human influence-related issues. An automated method for obtaining the reference angles would decrease these error influences. The applicability and accuracy of a camera-based underwater 3D motion capture system was analyzed by Silvatti et al. [18] and could be used for future studies.

Furthermore, the accuracy could be increased by improving the hardware components of the study. In the case of this work, the IMU hardware was attached with a temporary solution using a waterproof mobile bag, underwater camera housings and straps. Thereby, inaccuracies by slightly moving sensor hardware could not be avoided. For an advanced approach, waterproof sensor hardware could be integrated in the dive equipment in order to be placed at the exact same position for all divers for the whole dive without the necessity of bags or housings.

This study focused on the angles of the upper body and shanks. Although the obtained information can be useful for a training or feedback system for hobby divers, there is still a wide range of parameters to be established. Further angles as for example the hip angle and knee angle are of high importance and should additionally be measured in order to obtain a complete biomechanical model. Furthermore, the motion and influence of the fins have to be considered concerning several inclination angles but also their size and material.

V. Conclusion

In this study, we showed that an angular orientation determination of scuba diver's body and shanks is feasible in an underwater scenario. Data of ten divers were acquired including non-motion poses and defined fin kick scenarios. Based on the processing of inertial measurement data, automatic fin kick detection was proposed and applied to several fin kick intervals with a detection rate of 84.4 %. The angles of the upper body during non-motion phases could be determined with an accuracy of $0^\circ \pm 11^\circ$. The orientation determination of fin kicks was calculated for the absolute (in reference to the ground) and the relative (between fin kicks) orientation. The absolute and the relative fin kick angle showed errors of $0^\circ \pm 11^\circ$ and $0^\circ \pm 8^\circ$.

Based on this initial step towards the establishment of a biomechanical model for scuba diving, further studies can be conducted. The fin kick detection can be extended to identify kicks during the whole dive without pre-selecting fin kick intervals. Furthermore, the angular orientation determination can be extended to a three-dimensional system that not only provides the pitch angle of the diver's body. As a result, the proposed algorithm could be implemented in a training system containing waterproof sensors and an underwater data transmission. This system could analyze poses and fin kicks in real-time in order to establish a visualization or feedback device for divers or a training system for competitive sports.

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