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Short communication

An alternative illumination source based on LEDs for PIV measurements on human swimmers—A feasibility study

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ABSTRACT

Methods for flow visualization help to investigate the motion of fluids that are normally invisible. Especially, Particle Image Velocimetry (PIV) – with a laser as light source – has been established in the field of engineering and partly in biology. Since the standard measuring equipment applying a laser system is very sensitive with respect to transport, temperature, humidity as well as laser safety requirements have to be adhered, the observation and classification of flow pattern around human swimmers in swimming pools has been rarely applied. There is a need for a simple, powerful, affordable, robust, and portable illumination source which shall not harm the swimmer by exceeding the permitted maximum radiation for human skin and eyes. As a result, this technical note demonstrates an alternative light source system based on LEDs which enables PIV measurements around human swimmers similar to experiments with a (traditional) laser system. As an example, the flow fields of two different swimmers with a similar movement and phase are compared using both illumination methods laser and LED. Furthermore, a series of sequential velocity fields, produced by the motion of a monofin swimmer, generate a vortex pair with an inverse Karman vortex street which is typically seen in fish and marine mammal locomotion. Consequently, this LED illumination source is show to provide a sufficient suitable light intensity as well as light quality enabling the measurement of the flow field around swimmers.

1. Introduction

The methods of flow visualization facilitate to observe the motion of fluids that are normally not visible. Visual perception of the flow helps to understand the seen or recorded phenomena [1]. The development of Particle Image Velocimetry (PIV; e.g., [2,3]) allowes to combine the advantages of capturing the topology of flow with quantitative analysis. Applying this method to living creatures imposes special hurdles. The flow is highly unsteady, the movement hardly reproducible, particles must be nontoxic, and the illumination source should not disturb or harm the subject.

The PIV method is well established in the context of fish locomotion (e.g., [4–12]). In the pioneering days of PIV, simple projectors for illumination were used in combination with self-developed technologies and software programs to track particles (e.g., [4]). They allowed the first reconstruction of the wake behind a swimming fish on the basis of experimental recordings. In addition, the undulatory pump as well as the effect of flow preformation were firstly described [4]. Later, high powered continuous wave lasers were used as lightning source observing the flow of fish swimming in flow tunnels. Using standard 2D-2c-PIV, a single video camera triggered by the laser and orthogonal to the light sheet, produces two velocity components in the plane illuminated by the laser. For the observation of fast and unsteady effects time-resolved PIV (TR–PIV) is used with higher frequencies. Based on high-speed videos the obtained images are analyzed and post-processed using standard PIV cross-correlation techniques (e.g., [2,3]). As a result, the calculated matrix of velocity vectors estimates the flow in the light sheet [10].

With respect to sports the observation and classification of flow patterns is a routine diagnostic tool e.g. for rowing, cycling or winter sports. Paradoxically it finds its way into sport swimming only hesitantly. Due to the successful transfer of models from animal motion to

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sport swimming (e.g., [13,14]), the criteria for flow visualization can be applied on sport swimming. The transfer to less animal-motivated swimming styles is continued. Only recently there were publications in swimming related to flow measurements. These observed, for example, the direction and the movement of tufts fixed on the swimmer [15]. Furthermore, a layer of injected air bubbles was used to visualize the flow perpendicular to the swimming direction at 50 Hz [16–19]. The main drawback of the latter studies observing the vortices in the swimmer's wake can be seen in the use of air bubbles as particles. The speed of the rising air bubbles varies depending on its diameter. Small bubbles show the tendency to merge quickly and enlarge and rise faster to the water surface. Furthermore, the air bubbles occurred at different distances from the recording camera resulting in error-prone flow patterns and flow vectors [18,19].

Due to advances in measurement technology the visualization of the precise hydrodynamic conditions and the assessment of the flow pattern gained increasing importance to evaluate swimmer's performance, especially for the acquisition and visualization of the flow conditions induced by the swimmer (e.g., [20–22]). A group of scientists [23] used an approach applying a commercial PIV technique using a strong laser for illumination [20,23,24]. During this study the swimmer swam in a flow tunnel. Recordings focused on the flow around the hand area, behind a fin or in the wake of an undulating swimmer with an observation window of approximately 0.5 m × 0.5 m and a video frequency of 15 Hz. While swimming in a flow tunnel facilitates the technical application (stationary mounted laser), the safety regulations must be complied as well as the long-term functionality of the laser. Later and also based on PIV recordings in an indoor pool, [21] firstly the time-resolved vortex generation and transport in the vicinity of the swimming body and the interaction of subsequent segments with these vortices for an enhancement of the propulsion was documented [21,22, 25].

During the last years, in the establishment of light emitting diodes (LED) enhanced the light output [26] with simultaneous lower costs and allowed so called LED line lights consisting of a number of LEDs placed in line [27]. These LED illumination systems provide high intensity illumination for e.g. technical application [27], however for small observation windows only (e.g., up to 25 cm × 25 cm) and so far positioned outside of the water.

In summary, different methods for visualization (e.g., tufts, air bubbles) and calculation of flow fields (PIV) in the vicinity of a swimmer are available. Simple methods with tufts or air bubbles are cheap but error-prone and allow only low temporal resolution (frame rates lower than 200 Hz). More complex methods such as PIV enable to measure the flow fields with large frame rates (>250 Hz), however, they require very high costs, vulnerability of the setup, and strong safety regulations. The laser must be located outside of the pool to guarantee the safety of swimmers (high power laser with 380 V). In addition the environment should not affect the function of the sensitive laser. Dust, high air temperatures of above 30 °C, and high humidity above 60% are typical for swimming pools, but should be avoided with respect tot the laser functionality. Thus, a swimming pool with a spatially separated, dry laboratory with an underwater window is required. Since the laser beam has a very high intensity at the beginning of the expansion special precautions are necessary especially for the swimmer's eyes and for the swimmer's skin (e.g., [21,22,25]). Hence, the swimmers must wear laser safety goggles. The establishment of such a performance laboratory setup is principally possible, but only with a high financially and organizationally effort which is certainly only feasible in very few selective centers of sports excellence. Furthermore, especially qualified personal trained in laser systems is required. Procedures or applications which enable a wider and more effective usage in competitive sports located at several existing intensive training centers or in the animal world are currently not available.

The aim of this feasibility study is to provide a simple, powerful, affordable, robust and portable illumination source as an alternative for flow visualization. This illuminator system based on high power LED technology should be independent from the local conditions (swimming pool, underwater window) allows the usage of sophisticated PIV methods based on high-speed images, and requires only minor safety measures. The expected flow velocities around the swimmer require both high frame rates (≥250 Hz) and high spatial resolution [21]. The light section should cover an area of at least 1 m × 1 m and has a maximum thickness of 20 mm. The design shall ensure an easy transportation and a modular design to facilitate upgrades.

2. Material and methods

A system of 288 high power LEDs (LUXEON Rebel LXML-PE01-0100; Philipps Lumileds, The Netherlands; 3 mm width, 4.5 mm length and 2.61 mm diameter of the internal silicone lens) positioned in a line is used to create a homogeneous light section (Fig. 1C). The typical luminous flux of this LED is 180 lm (corresponds to the radiometric power of 260 mW) at 700 mA. The maximum spectral wavelength is 530 nm with a FWHM (full width at half maximum) of 30 nm and its typical forward voltage 3.15 V (maximum 3.99 V). Thereby, the spectrum of the green LEDs lies within the range of high transparency within the water, similar to the green laser usually used for PIV within water. Cylindrical lenses (LINOS N-BK7; Göttingen, Germany; length: 130 mm; width: 20 mm; focal length: 60 mm) collect the rays of light from LEDs and form a light sheet (Fig. 1B). An aperture slot with a width of 0.5 mm located between the line of LEDs and the cylindrical lenses limits the ray of light which falls onto the cylindrical lens and cuts off the ambient light. Vertical blends limit the rays of light in the longitudinal direction.

The whole illuminator system is constructed modularly. Six LEDs connected in series are integrated into one LED module powered by a single current regulator. Six of these LED modules are connected in parallel and are integrated into one lens module. The size of one lens module is based on the length of the cylindrical lens. Each lens module includes holders for the cylindrical lenses and vertical blends as well. The lenses are mounted at a distance equal to the focal length. The complete illuminator system (Fig. 1A) consists of eight lens modules (48 LED-modules; 288 LEDs) which create a light section of 1 m width and 20 mm thickness (Fig. 1C).

All modules and the corresponding constant current power supplies are placed in a water tight housing (Fig. 1A) with water proof connectors (IP68 sealed electrical cable connector; Buccaneer 900 Series; Bulgin, Tuningen, Germany). To ensure the safety standards for swimming pools a low-voltage galvanic isolated power supply (24 V DC) are used to isolate the current circuits in the water from the power network and supplies the illumination source under water via 30 m long cables.

In contrast to common PIV measurement with a double pulse laser we use a continuous light source and record images up to 250 Hz with different modes: The *basic* or *standby mode* at minimal current (280 mA per LED) is used for swimmer's orientation to see the light section. Just before the swimmer starts to swim the system can be toggled into the *measure mode* for 6–10 s with enhanced current (1500 mA) and higher luminosity. The system is actively cooled in order to avoid overheating and to reduce convective flow. This principle of two modes and the limitation of the duration of the high intensity light enhances the durability of the system as well as guarantees that the swimmers are not exposed above the maximum permissible radiation. All radiation power was measured by a laser power and energy meter (Nova II, Ophir Optronics Solutions, Jerusalem, Israel) at a wavelength of 530 nm in the air.

The subjects were informed about the methods, aims, risks, and safety regulations of the study and gave their written consent prior participation. The experimental setup of the original laser system as well as of the current LED system was assessed according to the applicable regulations, cf. Directive 2006/25/EC, IEC 62471 and IEC

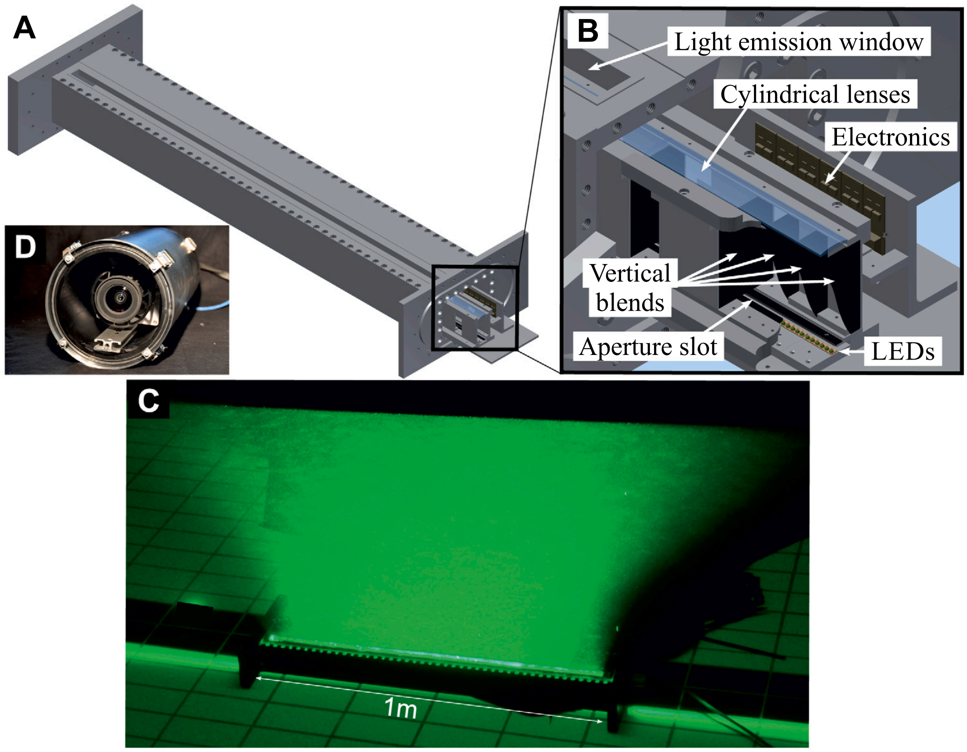

Fig. 1. (A) Total view of LED illuminator system and (B) detail-view on its components. The LED light passes through the aperture slot and the cylindrical lenses, before emitting through the window into the water. (C) The LED illuminator system, positioned on the bottom of a swimming pool, creates a homogeneous vertical light sheet of 1 m × 1 m × 20 mm usable for PIV measurements, e.g. on human swimmers. (D) Own underwater housing for the high-speed camera.

60825-1. The systems were found to be in compliance with the respective safety requirements and also approved by the ethics committee of the University of Jena (reference 1704-01/06).

For flow visualization, the path of the levitating particles (Vestosint 1121, Degussa, diameter 100 μm) illuminated by the vertical light section was monitored at 250 Hz with a high-speed video camera (Fastcam SA-3 60k, PHOTRON; San Diego, CA, USA). The high-speed camera can be positioned anywhere in the water using an underwater housing developed in-house. Local flow velocities were calculated in DynamicStudio 3.4 (Dantec Dynamics, Skovlunde, Denmark). After removing the static background for each frame (median filter; 5 × 5 pixels), for vector field calculating a cross-correlation algorithm was used (multi pass mode decreasing: 2 × (256^2, 50 % overlap) → 2 × (32^2, 50% overlap)), postprocessed (moving median filter; 5 × 5 pixels) and exported to Tecplot 360 2013 (Tecplot Inc.) for further graphical postprocessing. Assuming the final size of the interrogation area of 32 × 32 pixels (and a light section thickness of 20 mm) we used a seeding concentration of about 500 particles per liter (about 1 g/m^3; according to [28]). Both swimmers (with laser light as well as LED light) performed (after some preliminary experiments to adjust the swimming direction across the light sheet) approximately 15 m underwater with maximum speed at their preferred undulation frequency (similar to that described in [21,22]). For LED light measurements swimmers additionally wore a monofin. To avoid disturbing background by daylight and to increase the contrast of the particle images measurements were performed at night or in a darkened swimming pool, respectively. This enhanced the signal-to-noise ratio. Additionally, undesired reflections were suppressed by submerged black curtains.

In contrast to the laser where a thick light sheet diminishes illumination strength, in our system the thickness and the width of the sheet does not alter illumination density. The thickness of the light section is largely determined by the fixed aperture slot and the width of the cylindrical lenses and has to be determined in advance (current thickness: 20 mm). Due to the large size of the observation window (1 m × 1 m; 1024 × 1024 pixels) this thickness still fulfills the 'standard criteria', e.g., that the light sheet thickness should be significantly smaller than its height and width (in the order of 1%; [29]) and that the light sheet should be at least 10–20 pixels thick [30]. The chosen thickness enhances the probability of capturing the path of particles within the highly unsteady flow and is suitable for reconstruction of the flow patterns.

3. Results

The 288 LEDs positioned in a line create, in a distance of 1 m, a light sheet thickness of approximately 20 mm and an intensity (radiant power per unit area) of 9.30 mW/cm^2 (Table 1). The system can observe a region around the swimmer of at least 1 m width and 1 m height (Fig. 1C). Due to the modular design the observed region around the swimmer can easily widened by using multiple LED modules in a line.

Indeed, the LED illumination source does not fully attain the radiant power compared to a widened class IV high power laser (e.g., Nd:YLF laser; Litron LDY 303, wavelength λ = 527 nm, maximum output energy 20 mJ @1 kHz; [22]). However, the light intensity applied is sufficient to use PIV calculation algorithms similar to the use of laser illumination. It is robust in terms of transport and it is freely positionable (due to the 30 m long cables) in any swimming pool and therefore almost unrestricted in use An exemplary comparison of the PIV measurements using the laser and the LED-illuminator system (Fig. 2B) shows qualitatively similar results with respect to the PIV measurements (Fig. 2A). To demonstrate the suitability of the presented LED illumination, a monofin swimmer was observed as an example the change of the velocity fields due to the movement of the swimmer and its monofin was recorded (Fig. 3). These flow fields show (in extracts) a vortex pair with an inverse Karman vortex street between the vortices which is typical for fish and marine mammal locomotion [6,25,31]. Finally, the illumination system, presented here, currently costs less than 10,000 Euros and requires only a few safety regulations such as safety goggles for eye protection.

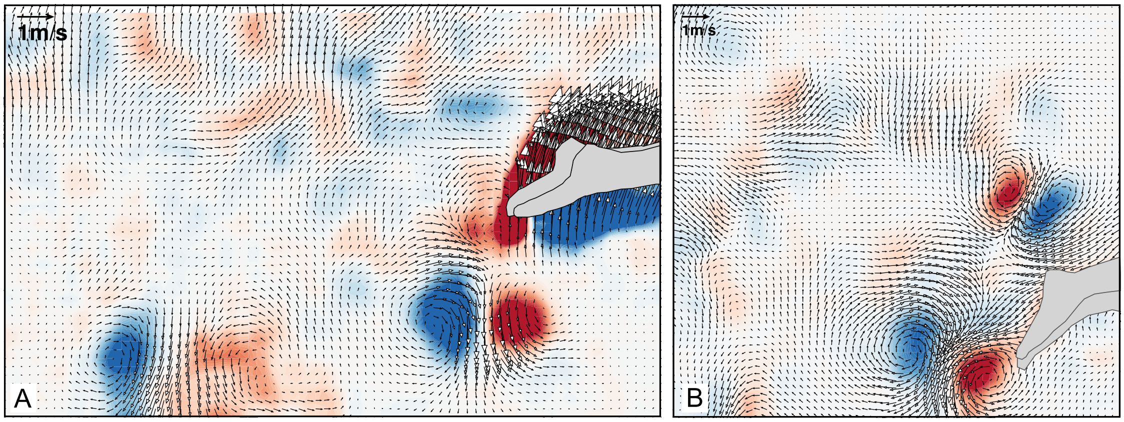

Fig. 2. Exemplary comparison flow fields (arrows represent flow velocity; contour colors stand for vorticity) between the different lightning sources (A: laser and B: LEDs) of different swimmers, but during similar movements and phases (after the down kick phase). The vector fields of both lightning sources (laser and LEDs) show similar results. The different image formats result from the different used high-speed cameras (A: PHANTOM V12; B: PHOTRON Fastcam SA3).

Table 1
Measured light intensity as a function of distance above the LED-illuminator system (measured in air) for 1 lens-module and 8 lens modules.

Distance[a]	Intensity[b] (mW/cm^2) of	
(m)	1 lens module	8 lens modules[c]
0.5	3.65	13.50
1.0	1.46	9.30
1.5	0.70	2.30

[a]Distance above the LED-illuminator system.
[b]Radiant power per unit area.
[c]The whole LED-illuminator system consists of 8 lens modules (total 288 LEDs).

4. Discussion

Here, we show the feasibility using LEDs for flow illumination and visualization. On the basis of high power LEDs a submergible light source was generated to create a homogeneous light sheet of 20 mm thickness for PIV experiments. This enables to observe the flow field within this light sheet without an expensive and technical sensitive laser system. The ease of use, mobility, robustness, low safety requirements, and low costs compared to current systems, such as the laser system, provide significant advantages and opens new fields of application.

Indeed, the comparison of different light sources for PIV experiments is not rather simple. Therefore, we consider the intensity, thickness (focusability), and spectral distribution of the light sheet. More precise statements about the measurement uncertainty only provides a direct comparison of LED and laser or information about the signal-to-noise ratio and the size of the particle image under comparable test conditions (observation field and its distance from the light source). Nevertheless, by using very light sensitive cameras monitoring the particles at a distance of about 1 m the flow field can be analyzed with standard software packages. Additionally, measurements in darkened pools can further minimize other interfering influences and improve the signal-to-noise ratio. The air bubbles exhaled by the swimmer interfering with the tracing particles, as they are significantly larger and brighter. In further studies, swimmers should try not to breathe out within the observation window, if possible, to avoid interfering air bubbles.

We decided to show a sequence of a monofin swimmer (Fig. 3), as it allows the comparison with literature and shows the suitability of the newly applied system. In contrast, the flow field image of swimmers without monofin is much more difficult to interpret, as both legs and feet are not closed or fused and thus do not represent a clear fin and as water can flow through the legs. Additionally, the 2D PIV represents one plane of the three-dimensional flow only [25] which further complicates the interpretation of the flow field. The sequence shown here corresponds to an inverse Karman vortex street with periodic vortex pairs. This is typical for active locomotion under water. However, due to the limited observation window only one vortex pair can be seen.

The abundance and quick development of high intensity LEDs may further enhance illumination power in the future. Surely, specifically designed customized optics would improve the luminous efficiency but also substantially increase the costs.

The possibility to increase power by shortening the illumination period (using ultra-short pulses of light) is limited. The selected long pulse with maximum power is quite sufficient for high-speed filming the moving swimmer. We decided to use the entire exposure time between two frames (4 ms) to maximize the light intensity of the raw images. Since luminous flux of the LED is close to saturation, the further reduction of pulse duration with the simultaneously increasing power of the pulse (for example for synchronization with each frame in high-speed filming) would not bring further advantages and would deteriorate the light intensity and brightness.

By exploiting its modularity intensity of the setup can be enhanced by superposition of sources from different directions arranged in a frame. Such a superposition also reduced the illumination gradient along the light sheet and prevents shadowing by the swimmer. In addition, using multiple light source modules and cameras, positioned side by side, the observation windows can be enlarged up to 2 m × 1 m and even larger. This enables the observation of the whole swimmer and its wake and perspectively facilitates to measure swimmer's total Karman vortex street. In this study exemplary only a section of the Karman vortex street was provided.

High power laser systems are extremely sensitive devices. In addition, the generation and guiding of the light sheet requires additional lenses and partly laser arms to be installed and finely adjusted. Any shock must be avoided and safety housings are necessary. The LED-system is rather shock prove and does not require an additional housing. In contrast to the laser, where high intensity ray is widened, the LED-sheet is generated by adding weaker sources. The repair is simple and economic due to the modular character.

One of the greatest advantages of the system is that the system is robust and encapsulated in a water-proof housing (IP68 standard) and completely independent from any other conditions (e.g., underwater window, electrical three-phase connection). This allows to use the LED system in *any* given swimming pool and forms the basis for a standardized usage e.g. in human swimming performance diagnostics. Furthermore, the costs of the LED illuminator system, presented here, are considerably low compared to an equivalent high power laser system (approximately by a factor of eight till ten).

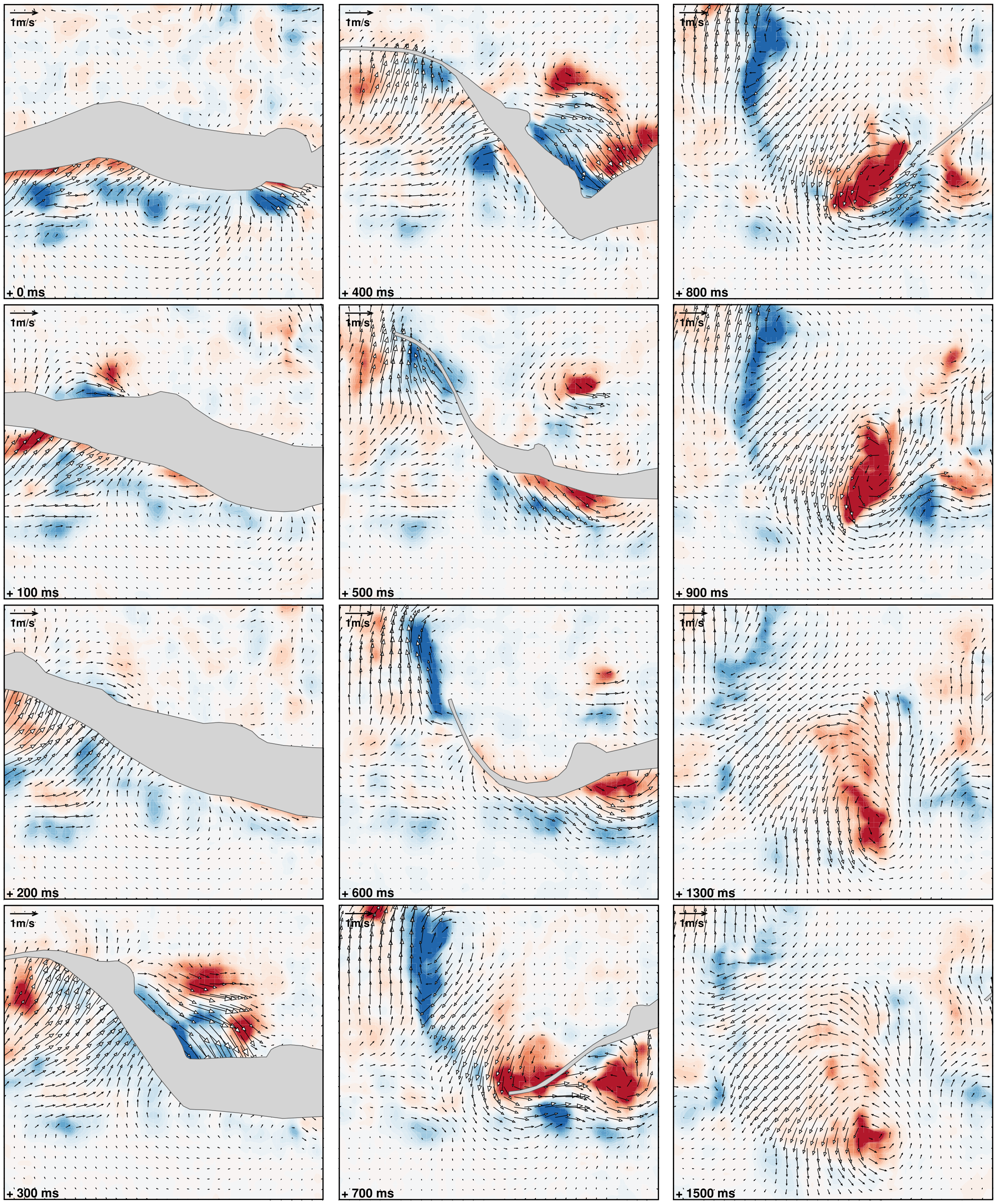

Fig. 3. Exemplary series of sequential velocity field results demonstrating the changes of the velocity field produced by a monofin swimmer. The arrows stand for the local flow velocity and the contour colors represent magnitude and sign of the vorticity (blue: clockwise and red: counterclockwise).

Finally, the light beam generated by suitable lasers is extremely harmful to the skin and especially to the eyes. It is obvious, that such a system cannot be installed in standard pool. Users need special licenses to operate the laser and the swimmers need specific safety measures to reduce harm. For the LED-system certain safety measures need to considered, too. The power source (low voltage DC), which has to be galvanic isolated from the public electricity network, should be placed away from the wet area. Subjects of investigations should wear suitable safety goggles adjusted to the light intensity and to the applied wavelength spectrum. Beside these measures scientists or trainers can use the instrument with moderate system instructions.

In summary, this technology represents a new and simple technical setup to visualize, analyze and optimize the complex time dependent flow characteristics including its generated vortices, e.g. during human swimming. The development of an affordable and mobile application with a robust light source enables to study fluid dynamics and the interaction between swimming body, movement and obtained flow around swimmers. The LED application can be used in all performance and diagnostic centers as a powerful diagnostic tool to support training methods for competitive swimming.

Further applications outside human being can be seen in biology, e.g., to investigate marine mammals such as dolphins or seals. Here, the LED illumination system can be used for flow visualization of free swimming marine mammals in marine reserves or in experimental basins. Furthermore, the system has the potential to imposingly visualize the flow of animals in large aquariums of zoo as a special effect for the visitors.

CRediT authorship contribution statement

Stefan Hochstein: Conceptualization, Methodology, Software, Validation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Anvar Jakupov:** Conceptualization, Methodology, Data curation. **Jens-Uwe Schmollack:** Methodology, Validation, Investigation. **Daniel Sporer:** Software, Data curation, Writing – review & editing, Visualization. **Veit Wank:** Resources, Writing – review & editing, Supervision, Funding acquisition. **Reinhard Blickhan:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

[1] W. Merzkirch, Why making use of flow visualization? J. Flow Vis. Image Process. 19 (2) (2012) 161–177.
[2] C. Willert, M. Gharib, Digital particle image velocimetry, Exp. Fluids 10 (4) (1991) 181–193.
[3] M. Raffel, C. Willert, J. Kompenhans, et al., Particle Image Velocimetry: A Practical Guide, Springer, 2013.
[4] R. Blickhan, Biomechanik der Axialen Aquatischen und Pedalen Terrestrischen Lokomotion, Habilitationsschrift, Universität des Saarlandes, Saarbrücken, Germany, 1992.
[5] U. Müller, J. Smit, E. Stamhuis, J. Videler, How the body contributes to the wake in undulatory fish swimming flow fileds of a swimming eel, J. Exp. Biol. 204 (2001) 2751–2762.
[6] U. Müller, E. Stamhuis, J. Videler, Riding the waves: the role of the body wave in undulatory fish swimming, Integr. Comp. Biol. 42 (5) (2002) 981–987.
[7] J. Liao, D. Beal, G. Lauder, M. Triantafyllou, The Kármán gait: novel body kinematics of rainbow trout swimming in a vortex street, J. Exp. Biol. 206 (2003) 1059–1073.
[8] E. Tytell, G. Lauder, The hydrodynamics of eel swimming: I. Wake structure, J. Exp. Biol. 207 (11) (2004) 1825–1841.
[9] E. Tytell, The hydrodynamics of eel swimming: II. Effect of swimming speed, J. Exp. Biol. 207 (19) (2004) 3265–3279.
[10] G. Lauder, E. Tytell, Fish Biomechanics, Vol. 23, Elsevier, 2005, pp. 425–468, Ch. Hydrodynamics of undulatory propulsion.
[11] J. Liao, A review of fish swimming mechanics and behaviour in altered flows, Phil. Trans. R. Soc. Lond. B 362 (2007) 1973–1993.
[12] U. Müller, J.G. van den Boogaart, J. van Leeuwen, Flow patterns of larval fish: undulatory swimming in the intermediate flow regime, J. Exp. Biol. 211 (2) (2008) 196–205.
[13] B. Ungerechts, A comparison of the movements of the rear parts of dolphins and butterfly swimmers, in: A. Hollander, P. Huijing, G.D. Groot (Eds.), Biomechanics and Medicine in Swimming, Human Kinetics., 1982, pp. 215–221.
[14] B. Ungerechts, U. Persyn, V. Colman, Application of vortex flow formation to self-propulsion in water, in: Biomechanics and Medicine in Swimming III. Proceedings of the VIII International Symposium on Biomechanics and Medicine in Swimming, Jyväskylä, 1998, 1999, pp. 95–100.
[15] J. Hay, A. Thayer, Flow visualization of competitive swimming techniques: The tufts method, J. Biomech. 22 (1) (1989) 11–19.
[16] R. Arellano, Vortices and propulsion, in: R. Sanders, J. Linsten (Eds.), SWIMMING: Applied Proceedings of the XVII International Symposium on Biomechanics in Sports, 1999, pp. 53–65.
[17] R. Arellano, S. Pardillo, A. Gavilan, Underwater undulatory swimming: kinematic characteristics, vortex generation and application during the start, turn and swimming strokes, in: K. Gianikellis (Ed.), Proceedings of the XXth International Symposium on Biomechanics in Sports, Universidad de Granada, 2002, pp. 29–41.
[18] J. van Houwelingen, R.P.J. Kunnen, W. van de Water, A.P.C. Holten, G.F. van Heijst, H.J.H. Clercx, Flow visualisation in swimming practice using small air bubbles, Sports Eng. 22 (2) (2019) 1–8.
[19] J. van Houwelingen, A.P.C. Holten, H.J.H. Clercx, R.P.J. Kunnen, J. Molenaar, W. van de Water, Visualizing large-scale flow using synthetic aperture PIV, Exp. Fluids 61 (1) (2020) 1–14.
[20] T. Miwa, K. Matsuuchi, H. Shintani, E. Kamata, T. Nomura, Unsteady flow measurement of dolphin kicking wake in sagittal plane using 2C-PIV, in: J. Vilas-Boas, F. Alves, A. Marques (Eds.), Proceedings of the Xth Congress of Biomechanics and Medicine in Swimming, 2006, pp. 66–68.
[21] S. Hochstein, R. Blickhan, Vortex re-capturing and kinematics in human underwater undulatory swimming, Hum. Mov. Sci. 30 (5) (2011) 998–1007.
[22] S. Hochstein, S. Pacholak, C. Brücker, R. Blickhan, Experimental and numerical investigation of the unsteady flow around a human underwater undulating swimmer, in: C. Tropea, H. Bleckmann (Eds.), Nature-Inspired Fluid Mechanics, Vol. 119, Springer, 2012, pp. 293–308.
[23] K. Matsuuchi, T. Hashizume, Y. Nakazawa, T. Nomura, H. Shintani, T. Miwa, Flow visualization of unsteady flow field around a monofin using PIV, in: J. Vilas-Boas, F. Alves, A. Marques (Eds.), Biomechanics and Medicine in Swimming X, Portuguese Journal of Sport Sciences, 2006, pp. 60–62.
[24] K. Yamada, K. Matsuuchi, T. Nomura, J. Sakakibara, H. Shintani, T. Miwa, Motion analysis of front crawl swimmer's hands and the visualization of flow fields using PIV, in: J. Vilas-Boas, F. Alves, A. Marques (Eds.), Biomechanics and Medicine in Swimming X, Portuguese Journal of Sport Sciences, 2006, pp. 111–113.
[25] S. Hochstein, Widerstands- und Strömungsbeeinflussung der Menschlichen Undulatorischen Schwimmbewegung (Ph.D. thesis), Westfälische Wilhelms-Universität Münster, Germany, 2013.
[26] C. Willert, B. Stasicki, J. Klinner, S. Moessner, Pulsed operation of high-power light emitting diodes for imaging flow velocimetry, Meas. Sci. Technol. 21 (7) (2010) 075402.
[27] W. Bakker, F.I.H. Verhaart, A. de Fockert, G. Oldenziel, Pulsed light emitting diodes for particle image velocimetry in a vertically submersible pump, in: 38th Int. Association of Hydraulic Research World Congress (Panama City, Panama, 1-6 September), 2019.
[28] R.J. Adrian, Particle-imaging techniques for experimental fluid mechanics, Annu. Rev. Fluid Mech. 23 (1) (1991) 261–304.
[29] C. Tropea, A. Yarin, J. Foss, Handbook of Experimental Fluid Mechanics, Springer, 2007.
[30] B. Wieneke, S. Taylor, Fat-sheet PIV with computation of full 3D-strain tensor using tomographic reconstruction, in: 13th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, 2006, pp. 26–29.
[31] M. Sfakiotakis, D. Lane, J. Davies, Review of fish swimming modes for aquatic locomotion, IEEE J. Ocean. Eng. 24 (2) (1999) 237–252.