Dynamic Scanning of Cyclists: Techniques and Applications

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https://doi.org/10.15221/23.52

Abstract

Technological advancements in human body modelling have experienced significant growth in recent years. A prime example is the MOVE4D system by IBV. This system combines scanning and post-processing techniques to generate watertight 3D meshes of the human body in motion, thereby opening up numerous possibilities and applications in various fields, including the analysis of anthropometric features on the articulating human body. One limitation of the MOVE4D system is that it is unable to create watertight meshes when a subject and an object are scanned together. This issue arises when registration techniques used on a homologous mesh yield deviations from the true shape of a human, with the initial point cloud containing an articulating human together with points of an object supporting the articulation. This bottleneck is currently limiting further exploration of object-assisted human movement, as applied in fields including sports sciences and occupational ergonomics. In this study, a subject is scanned while cycling, at a rate of three frames per second, to present a technique that discards the bicycle and captures only the human subject. The resulting avatar of the cyclist is a valid representation of the articulating cyclist. Discarding the bicycle is achieved by using an infrared-absorbing black coating on a bicycle template that successfully inhibits the MOVE4D IR camera's ability to capture the bicycle template. In addition, the specific very low surface area of the geometry of the bicycle template allows the MOVE4D system to accurately capture the cyclist's body in its entirety. This coating yields very promising results that could not be achieved with the other option explored in this article: removing the bicycle algorithmically through a post-processing step. Two initial applications of our technique are presented, demonstrating how to retrieve dynamic anthropomorphic features and aerodynamic drag simulations.

Keywords: 4D scanning, Cycling, Object removing 4D, Anthropometry

1. Introduction

The manuscript should be written in English, not have headers, footers, or page numbers. It should be in a one-column format and be 6-12 pages long. It may include color images, which will be visible in the electronic form of the proceedings; the hard copy will be printed and published in black and white.

Science around cycling has been growing consistently, pushing the boundaries of cycling performance aligned with roadmaps for technological innovation. The improvement and investigation of cycling has become an important field of applied research, as the bicycle is currently used by a broad spectrum of cyclists: from elite athletes in UCI pro-tour cycling, mountain biking, and triathlons to functional use as a means of transportation and exercise. Research and innovation in the cycling domain have supported the development of many other technologies in various fields, including ergonomics, aerodynamics, physiology, biomechanics, material strength and drivetrain efficiency. Many of these applications use digital models of cyclists, especially in relation to aerodynamics and performance optimization[1], ergonomics and safety [2], and the design of cycling garments [3]. Although cycling is inherently a dynamic activity in which aerodynamics play a major role, no studies have taken up the challenge of considering all the various changes in posture that occur during the dynamic cycling movement. In addition, ergonomics, safety and garment design are restricted to the incorporation of static measures into new designs. For helmets, it is natural to inoculate designs on static measurements. For garment design, however, key anthropometric features may vary along with cycling position.

The analysis of dynamic measurements is impeded by two important bottlenecks: 1) lack of accuracy and ease of operation for 4D body scanners (which are currently being resolved) [4] and 2) the presence of a bicycle, which was already hampering the static 3D scanning of cyclists [5]. It also poses a major burden to 4D scanning, which requires a resource-efficient method for processing and registering a bulk of 3D scans into a homologous mesh.

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Removing the bicycle from the 4D scan in the very first step of the construction of digital human models makes it possible to perform in-depth biomechanical and shape analysis of the human body when cycling. This can allow the technology of human 4D scanning to become a new and innovative medium for investigating the cycling movement and many aspects related to it. Moreover, the present technique can be applied in various other activities in which human movement is guided or constrained by external objects to capture only the human.

The 4D scanning of humans is a recent development within the field of digital anthropometry [6]. It allows the valid mapping of the 3D geometry of an articulating human body as samples through time. This creates numerous possibilities for investigating human movement through digital body modelling. To obtain the human body models, this study utilizes the state-of-the-art MOVE 4D markerless motion-tracking system (Instituto de Biomécanica de Valencia -IBV) [7]. Based on modular photogrammetry, MOVE 4D is a 3D/4D capture and analysis system that automatically processes the point cloud of the human to provide watertight 3D meshes in motion [8]. Subjects are captured in the infrared (IR) spectrum.

The possibility of creating an accurate 4D model of pedalling cyclist creates new opportunities for performance assessments of cyclists, as well as the biomechanical and physiological modelling of cyclists. This new methodology offers benefits for the fields of both human anthropometry in movement and cycling.

First, 4D scanning adds value as a new and improved way of analysing the biomechanics and movement patterns of cyclists. Currently, the measurement and evaluation of a cyclist's body movements (e.g. trunk stability, upper body angle and leg kinematics) are performed using marker-based systems [9], [10], which are located in the physical world and thus subject to many limitations. For example, they require hand placement, which is susceptible to errors relating to placement position and falling off the skin, and they are often in conflict with the personal space of subjects [11]. Moreover, some of these marker systems are only one-sided or do not allow for the same freedom of movement. All these issues could be resolved using digital models generated by 4D scanning. Combined with digital trackers, digital models could make it possible to analyse the biomechanics and movement of cyclists. Digital trackers can be placed on any part of the digital model. This is not possible with systems based on physical markers.

Second, the MOVE4D system makes it possible to track **dynamic anthropometric measurements** of the human body through time [12]. Currently, anthropometric measurements are done only in pre-defined static positions. With the high accuracy (1 mm) of the dynamic measurements in MOVE4D, manufacturers of cycling clothing can use the system to develop their garments further, both for general design based on numerous models and individually based on the dynamic measurements of a specific person on a specific bicycle. For example, professional cyclists might want customized suits to increase their performance, something that is already being done, but only based on static measurements [3].

A third new opportunity offered by the 4D digital twin of a cyclist is in the field of **cycling aerodynamics**, which is a core focus in the high-performance cycling world [13], [14]. More specifically, knowledge of cycling aerodynamics is important to the advancement of computational fluid dynamics (CFD) analysis to assess a the aerodynamic drag of a cyclist [1], [15]. Currently, the model for CFD analysis is usually obtained by scanning a cyclist with a 3D scanner [15]–[17]. The possibility of doing CFD analysis starting from the homologous mesh of a pedalling cyclist in 4D would be a significant improvement, as it would reduce the current bias often found between static CFD analysis and the dynamics of outdoor and wind-tunnel testing[14], [18].

Finally, the creation of a large 4D dataset of moving cyclists could facilitate the investigation of many aspects of cycling within the human population. Having a large number of 4D models of cyclists could thus be of benefit to the broader market surrounding cycling (e.g. clothing manufacturers, bicycle manufacturers).

In addition to creating new opportunities in the cycling world, the ability to scan and obtain an accurate homologous mesh of a moving cyclist could open the door to using 4D scanning in countless other applications with moving human-object interactions (e.g. golf, tennis, ice skating and skiing). Currently, however, these applications and opportunities are restricted by the limitations of the MOVE4D system and its inability to scan or remove objects, as shown in [11].

When an object is detected by the MOVE4D system, no usable or accurate homologous mesh can be computed. This is because the system was developed with the aim of scanning human bodies in motion. A bicycle is not scanned accurately, for several reasons. First, the same processing pipeline/methodology for obtaining a watertight and accurate homologous mesh is based on a human template, and not on a template for objects. Second, the object's material properties or coating might be IR-absorbing, and thus discarded by the optical sensors of the Move 4D scanner. Third, unlike with humans, if the camera's view of an object is blocked by the person or another object, no homologous model of the object will be created to fill in the blanks.

This article describes a new method for using the current MOVE4D system to eliminate these obstacles and to obtain an accurate homologous scan of the cyclist, thereby opening the door for further research on applications in the cycling world, as mentioned above.

In addition to the aforementioned methods for overcoming the obstacles of the human-object capturing, this article introduces two direct applications as preliminary results of the present method: 1) dynamic measurements and 2) the first steps towards easily implementable simulations of cycling aerodynamics.

2. Materials and Methods

A stationary bicycle with a very elementary geometry connecting adjustable contact points—handlebars, saddle and pedals—was used in all experiments. The small volume of this stationary bicycle minimizes blockage for the cameras while capturing the human. It can also be easily coated (Figure 1).

Two methods are proposed for separating the subject from the bicycle, as described below.

2.1. Visible bicycle: Object removal in post-processing

The first method for reducing the object from a 4D scan dataset involves the post-processing of the scan data. During the 4D scanning process, point clouds are stored with colour values associated with them. The values are defined in the red–green–blue–alpha (RGBA) channel colour space. By applying a colour filter, the objects can be either removed from the given coloured point cloud or stored separately. For this method, the stationary bicycle is uniformly coloured red, as shown in Figure 1. A static scan is performed with the MOVE4D scanner, and the point cloud is then filtered by the RGB colour: (195, 40, 57). The Alpha-channel value generated during pre-testing had very litter influence on the filtering results, and it is thus negligible in the following study. The filter was applied with tolerances around the selected colour value. The point cloud was searched for points with a colour value of +/- 25 (tolerance 1) or +/-50 (tolerance 2). Values less than zero were set to zero. After applying both filters, the two point clouds were compared to identify the effects of the respective tolerances on the filters.

Fig 1: Cyclist on red bicycle in 4D scan lab

2.2. Undetectable bicycle

The second method of creating a usable scan from a pedalling cyclist involves capturing the scene using a bicycle that is undetectable to the MOVE4D system [14]. The assumption is that, if the MOVE4D system does not detect the bicycle, it will generate only a raw point cloud of the cyclist. From this, the software can compute a usable homologous mesh immediately, without any additional manipulations of the raw point cloud or non-homologous mesh.

From [11], we know that coating an object in a certain IR-absorbing black (Dupli-Color 693854) shows promising results, as it was not detected by the system when used on a hand-held aluminium bar. The coating does not reflect IR light emitted from the cameras, which are somewhere within the broadband of 3-14µ, making the coated object invisible to the IR cameras of the MOVE4D system.

The stationary bicycle was coated with Dupli-Color 693854. The scans were repeated twice: first in cycling clothing and a second time in a body-covering green suit.

2.3. Dynamic measurements

The most recent update to the MOVE4D system includes the ability to perform anthropometric measurements on a dynamically moving homologous mesh [12]. The challenge is thus to reproduce a valid homologous mesh of a cyclist. During the cyclist's pedalling motion, muscles contract to exert force on the pedals. If we could obtain a high-resolution, dynamically moving, valid and watertight homologous mesh, it would be possible to monitor the contraction of the muscles in the thigh during the pedalling motion, thus providing proof of principle for the validity of our homologous mesh.

The input for the dynamic measurements was a six-second scan at 3 FPS, resulting in a total of 19 frames. The number of frames was kept low for faster computing and processing of the scan. The maximal girth and thigh girth midway between the hip and knee joints was then computed inside the MOVE4D software.

2.4. Cycling aerodynamics: CFD analysis

To verify that the homologous mesh can be used to perform computational fluid dynamics (CFD) analysis, a 3D model (i.e. one frame of the 4D scan) is used to create the model needed for a steady-state CFD analysis. The 3D model of the cyclist and a separate 3D model of a racing bicycle are imported into the software. Boundary conditions (e.g. wind speed and rotating wheels). A mesh dependency study is performed to obtain a reliable result. Visuals and measuring points are used to evaluate the drag values of the model.

3. Results

3.1. Visible bicycle: Object removal in post-processing

The results of filtering an object according to a defined colour value are displayed in Figure 2. It shows the original point cloud and two filterings, each with a different tolerance level. As shown in Figure 2(c), which is based on the larger tolerance setting, a larger part of the red bicycle is filtered, although some parts of the bicycle with white or very dark red colour values remain. The reason why the whole bicycle could not be filtered is that the red bicycle, which was coated evenly in red, does not display an evenly scanned red colour in the raw point cloud. As clearly illustrated in Figure 2, even though the red bicycle had an even colour (see Figure 1), the coloured point cloud captured and processed by the scanner displays clear differences in homogeneity. The reflective properties of the metal with the red paint cause difficulty in the ability to scan the right colour for the MOVE4D system. Because of the reflections on the bicycle, some areas appear white, and others are dark. The entire colour spectrum between white and dark red is thus present on the object to be removed.

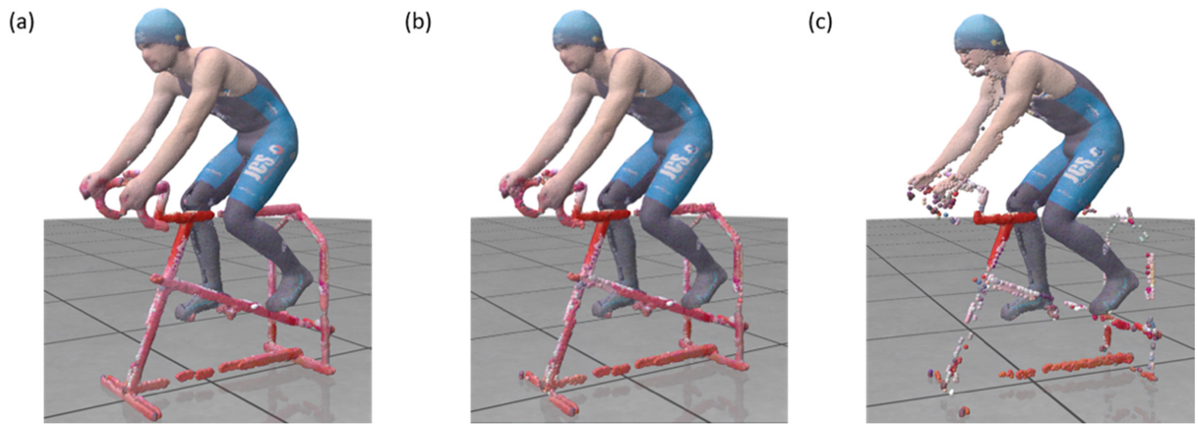

Fig 2: Results of filtering a 4D Scan using a colour filter: (a) original point cloud, (b) filtering Tolerance of +/- 25, (c) filtering tolerance of +/- 50.

In addition, the red colour spectrum of the bicycle also corresponds to the colour values of the skin of the test subject. If the threshold of the red colour to be filtered is increased, parts of the cyclist will also be filtered, and thus removed, as illustrated in Figure 3.

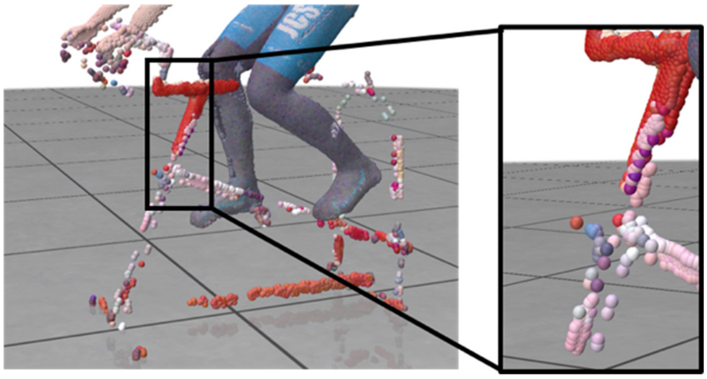

Fig 3: Post-processed scanned coloured bicycle with large tolerance, highlighting problems of reflection.

3.2. Undetectable bicycle

The results indicate that the IR-absorbing black coating successfully inhibits the MOVE4D IR camera's ability to capture the bicycle. Even though some parts of the lower extremities are sporadically blocked by the bicycle and limb moving on the opposing side, post-processing can achieve an accurate full-body homologous mesh. The raw point cloud displays several minor detections of the bicycle around the saddle and pedal area, likely because these areas were not fully coated with the IR-absorbing black coating. In the homologous mesh (Figure 4), there are almost no deformations caused by the stationary bicycle. The area around the seat post and saddle did display some minor deformations, likely because the saddle area was not fully coated. A different IR-blocking material or coating should be used for the saddle.

Fig 4: Raw point cloud of black bicycle scan (left) and its non-textured homologous mesh (right).

3.3. Dynamic measurements

The dynamic measurements of the pedalling cyclist's thigh were computed in two locations, both in the middle of the thigh and where the girth is maximal (Figure 5). Even without substantial power being delivered by the subject, as no resistance was exerted on the stationary bicycle, the cyclic nature of the movement is clearly visible.

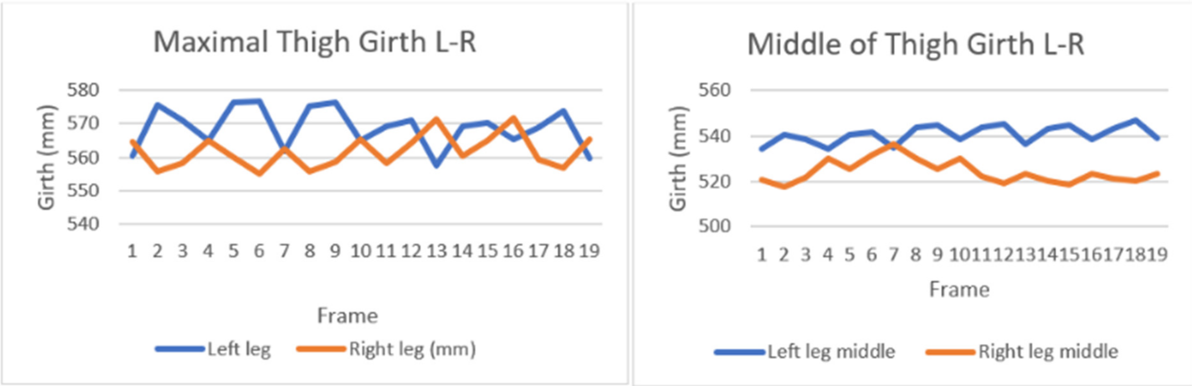

Fig 5: Dynamic measurements of thigh during cycling motion: maximal girth (left) and middle girth (right)

3.4. Cycling aerodynamics: CFD analysis

The raw data of a single scan were acquired in a millisecond. The resulting homologous mesh was obtained by the software. The mesh of the second method was successfully joined with another bicycle (Figure 6). This provides proof-of-concept that the files exported from the MOVE4D system can be used to create a model for CFD analysis. Other objects with known geometry (e.g. helmets or bicycle attachments) can be merged with the model, so the standalone human figure can be used to evaluate their aerodynamic properties.

A CFD analysis of the current 3D model shows the turbulence energy (Figure 7) and the speed and direction of air particles around the cyclist (Figure 8).

Fig 6: Homologous mesh joined with an elementary racing bicycle.

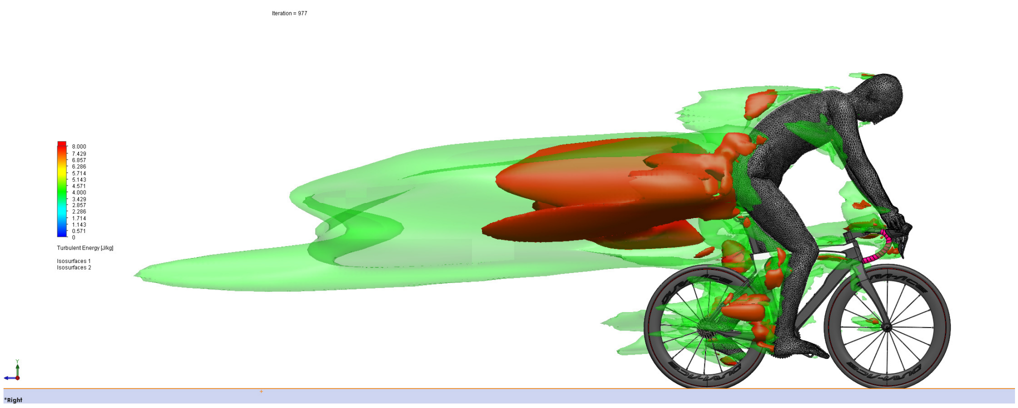

Fig 7: Turbulence energy of a cyclist

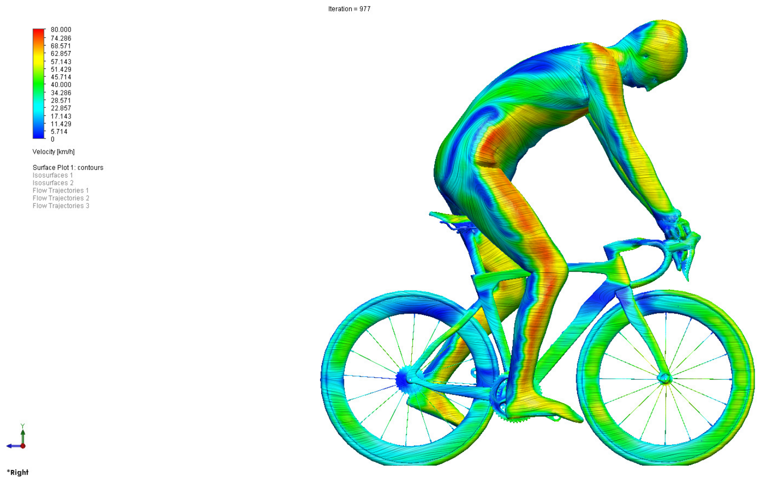

Figure 8: Pressure distribution of a cyclist

4. Discussion

The first methods for removing the bicycle in a 4D scan of a pedalling cyclist have yielded unexpected yet insightful results.

The first method, in which the bicycle is painted red and scanned with the human and then removed in post-processing did not generate results that could be used in further applications. More specifically, the red could be reflected, as it might be in the skin tone of the subject, and the shiny character of the paint on the metal causes too much reflection and loss of homogeneity. In follow-up studies, it might be interesting to use a green bicycle with a matte finish to improve results (c.f. a green screen in animation techniques). With a matte green colour, the filter tolerance could be increased without overlapping with the subject's skin, thus retaining more data of the human body's point cloud. Skin-specific verifications of this techniques are recommended.

Given that different colours can be filtered, this method would be more versatile than coating objects, as in the second method, which could be regarded as a non-destructive scanning process (e.g. eliminating the need to paint an expensive bicycle). Colour filtering might allow for specific object removal to suit specific applications, even in the unprocessed raw data of the point cloud.

The second method, using the invisible black bicycle, yielded unexpectedly positive results. The bicycle was almost completely undetected by the MOVE4D system. Although some areas still displayed difficulties and inconsistencies, this was due primarily to insufficient coating. Further exploration into how this coating can be applied non-permanently is needed, as cyclists might want to perform these scans on more complex bicycle geometries (e.g. their own bicycles) in a non-destructive process.

Given that the black coating allowed the software to create a homologous mesh, the feature of dynamic anthropometric measurements could be explored. In this study, these measurements indicate an accuracy of 1 mm, as the graphs of the left and right leg moved consistently in the opposite direction, as expected during the cycling motion. In addition, there was a slight, consistent size difference between the left and right legs. This size difference also recurred during manual measurement of the girth of the cyclist's legs in the resting position, where the girth of the left leg was measured to be 6 mm more.

This new ability to visualize measurements on the articulating human body of a cyclist and to analyse these measurements can have many applications, as mentioned in the introduction. The method for constructing digital cycling twins with scans captured in split-second or dynamic body scans also offers opportunities in cycling aerodynamics. As illustrated in Figures 7 and 8, the body scans can be used for computational fluid dynamics. The possibility of accurately simulating a moving 3D model in a CFD simulation solves one of the greatest current discrepancies between CFD analysis and real-life testing (e.g. wind-tunnel and field testing): the effect of the moving legs, which is not taken into account in simulations with static 3D models. The 4D digital twin of a cyclist in motion thus brings CFD analysis another step closer to the simulation of outdoor cycling. For example, CFD analysis in motion could be used for ultra-personalized design of time-trial bicycles, where both the human and the bicycle can be modelled in motion together to obtain optimal drag values. The proof of principle for capturing the underlying data—the finding that we could acquire a scan suited for CFD in a millisecond—should be subject to further calibration and validation. To this end, results should be benchmarked against wind-tunnel experiments and velodrome tests.

Although the current method of coating a stationary bicycle with elementary geometry and a frame with a small surface area was sufficient for the present proof of concept, it is subject to limitations that must be resolved for further applications. First, a 'one-bike-fits-all' without any resistance on the pedals is not yet usable for assessing anthropometry when power is exerted, which is particularly desirable in the analysis and optimization of high-performing cyclists. The possibility of obtaining accurate digital twins of cyclists thus also entails a need for stationary bicycles that can accurately mimic the biomechanics of the subject and that can be deployed in the same lab. This raises questions concerning the best way to organize non-permanent hiding articulation-assisting objects of various shapes from the MOVE4D scanner. Such processes could also be useful for other applications in the areas of sports, occupational ergonomics and contemporary anthropometry [Spahiu, T., & Kyosev, Y. (2023). 59 Compression Clothing and Body Deformations Through High-speed 4D Scanning. In *Compression Textiles for Medical, Sports, and Allied Applications* (pp. 59-70). CRC Press.].

Our technique has been verified by capturing the left and right tight girth of the subject and visually determining whether these measures behave as intended. Further accuracy and validation assessments are required. This could possibly be arranged through tape measurements or calibrated strain gauges.

In conclusion, the experiments conducted in this study have resulted in the development of a new method for creating seemingly valid 4D homologous models of moving cyclists. Further validations are nevertheless required. To date, the presence of an object (in this case, the bicycle) has formed a bottleneck impeding the creation of airtight, highly accurate 4D models, thereby preventing further exploration of the cycling movement.

This innovation in scanning with the MOVE4D system opens doors to future work in the area of cycling, as well as in other fields, in order to obtain valid models of human-object interactions. First, as introduced in this article, these new digital twins can be used in cycling research for various applications (e.g. CFD analysis and dynamic anthropometric measurement) and for the further development of technology and expertise concerning cycling (e.g. biomechanics, equipment and ergonomics). Second, these results can be extrapolated to other sports or human-object interactions in a wide variety of fields, ranging from high performance in sports to physical revalidation after trauma, the assessment of walking aids for the elderly.

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