Investigation of the Interaction between Protective Clothing and Body During Motion Actions with Integrated Multisensory Scanning System 4Dsense

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Abstract

In times of societal change toward an environmentally conscious and sustainable community, bicycles are increasingly becoming the key to personal transportation. Bicycling and other high-speed sports such as soccer, field hockey, and volleyball often result in abrasions. These occur through the dual mechanisms of friction and shear forces. To avoid this, protective elements are usually integrated into the sportswear at the joints. However, since the joints are always the point of maximum garment displacement, accurate placement of the protective elements is an important prerequisite for the protective effect. The objective of this work is to investigate the extent to which relative displacement occurs between the joint and the protective element during typical application movements.
For achieving this objective, different types of sensor techniques must be applied simultaneously. The complete system, named *4Dsense* was build on the basis of the Move4D scanner (produced by IBV) for photogrammetric scanning, which was integrated with the electromagnetic VIPER System of company Polhemus for direct absolute position tracking and with pressure measurement system TexSens®-G. 4DSense provides information about the motion of the clothing or the human surface, the coordinates of several points under the surface and the pressure between the clothing and human body on selected positions. The first results of the application of this multi-sensory system 4DSense for the investigation of protective clothing shows that the combination is very promising and provides information with additional dimensions and quality, which will help the clothing developers to provide protective clothing with improved wearing comfort during motion.

Keywords: 4d body scanning, 4Dsense, dynamic fit, protective clothing, relative movement

Introduction

Sport and physical activity play a crucial role in promoting overall health and well-being. However, the incidence of accidents leading to injuries remains a concern for cyclists and other athletes. To mitigate these risks, the use of protective gear is essential. Presently, only select protective equipment is widely adopted by the general public.

Cyclists have shown increasing reliability in wearing helmets, yet joint protectors, such as knee and thigh guards, are not as prevalent. For instance, in soccer, the use of shin guards is standardized, while knee and thigh protectors are rare, despite being the most frequently injured body regions during the 2019/20 season. The primary function of protective gear is to protect specific body areas, often employing rigid materials with high strength, such as various plastics. Factors like thermophysiological comfort and freedom of movement are of secondary importance. [1–3]

To address these concerns, current products utilize multi-layered structures comprising foams and other impact-absorbing materials, overcoming the limitations of traditional designs [4]. Additionally, the implementation of non-Newtonian fluids and various foams has become standard practice [5]. Employing multi-layered knitted fabrics with tailored material combinations aims to reduce shear and impact forces to a level safe for the skin tissue in the event of an accident. Each layer progressively diminishes the applied stresses, ultimately minimizing the forces transmitted to the skin. Therefore, it is crucial to ensure that such protective elements integrated into athletes' clothing effectively act on the intended areas. Movements change the curvature of the body surface. This is particularly the case near joints [6]. In interaction with the friction between body and clothing, the protectors can move away from the surface to be protected. This must be taken into account in the design of the protective elements. The problem has already been studied for the construction of motorcycle suits, the objective of this research is to develop a generally applicable rule for this purpose [7].

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The experiments are conducted using the 4Dsense System, which is a combination of a state-of-the-art 4D scanner capable of capturing movements at a high frame rate and the Viper System developed by Polhemus, a multisensor system for motion tracking. This research investigates the relative motion between protective gear and the wearer. During a body scan, appropriate protective equipment is worn, and sensors are strategically placed underneath. Correlating the data from the sensors and scans yields valuable insights into the relationship between movement, elastic deformation, and displacement of the sportswear.

Through comprehensive analysis, this study seeks to enhance the design and performance of protective equipment, optimizing their effectiveness in safeguarding athletes during various sporting activities. By combining scientific approaches and advanced material technologies, the ultimate goal is to minimize the risk of injuries and support athletes in their pursuit of a healthy and active lifestyle.

Methods

The *Move4D Scanner* is a system developed by the Institute for Biomedical Engineering in Valencia (IBV) for three-dimensional object capture with motion recording capabilities. The Chair of Development and Assembly of Textile Products at TU Dresden possesses such an installation, this is shown in the module and overall structure. Within the necessary scanning laboratory, twelve individual modules are installed, each functioning as a 3D scanner independently, facilitated by an Infrared (IR) projector and two IR cameras. Additionally, an RGB camera per module allows the capturing of color and texture of the scanned object. As a result of this setup, a scanning area of 2500x2500 mm is achieved, allowing for the recording of any movements. The maximum capture speed reaches 178 fps, with a resolution of 1. [8]

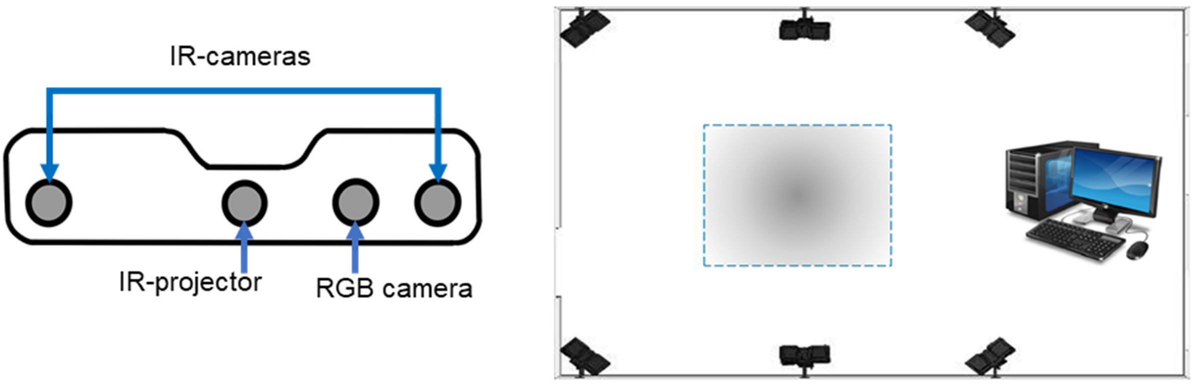

Figure 1: Move4D Scanning System

The utilized multisensor system, *Viper*, was developed by the company Polhemus. An electromagnetic field is generated using an emitter, and the sensors within it are detected to determine their positions. The system can handle up to 16 sensors simultaneously, with an update rate of 960 Hz and a latency of one millisecond. [9]

In this experiment, sport-specific leg movements are to be analyzed, as can be seen in

Figure *2*. In the first movement (

Figure *2* (A)), the participant brings his right leg ,from a straight standing position, upwards ,angles the knee and then brings it back to the straight position. The second movement (

Figure 2 (B)) complements the first with a horizontal rotation of the raised and angled leg. These movements represent the largest expected deviation of a protected joint, which is particularly relevant in soccer and cycling. Consequently, the greatest positional displacement of the protective element is to be expected at this point. In a recording session, each movement is performed twice.

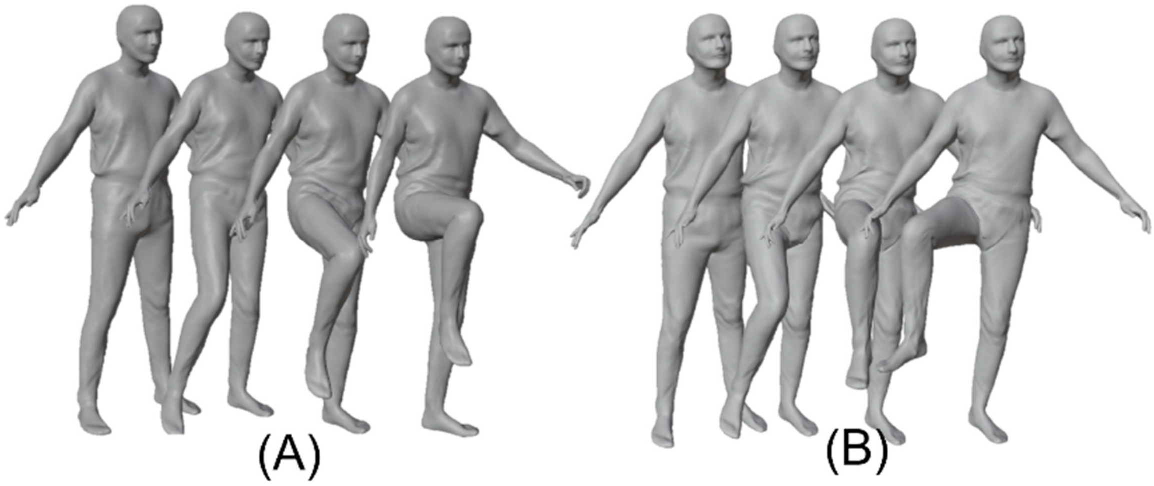

Figure 2: Examined Movements

In preparation for the experiment, patches are designed for the hip and knee and sewn onto a commercially available sports pants. These patches are composed of a material exhibiting enhanced protective properties against abrasions. Specifically, they are constructed from a fabric comprising 68% ultra-high-molecular-weight polyethylene (UHMPE) and 32% Kevlar. A grid with a resolution of 5x5mm is delineated on the patches to facilitate the subsequent optical detection of the sensors.

The sensors from Viper Systems are affixed to both the participant's skin and the pants, as illustrated in Figure 3. One sensor is placed on each of the knees and hips, after which the test person puts on the pants. Two further sensors are placed directly above these on the pants and fixed. After each recording session, the position of the sensors is checked. The sensors are fixed to the skin using dermatological adhesive material to prevent skin irritation. The sensors on the trousers are fixed with a polyvalent adhesive in tape configuration. The sensor cables are also fixed to the trousers to minimize inaccuracies in the scanning process.

The Move 4D system maintains the indices of the mesh points during a recorded movement. This allows tracking and recording the movement trajectory of individual points, for this purpose software developed at this chair is used. [10, 11]

For this experimental setup, 6 such points are defined: one on the hip, on the pelvis, two on the femur, one on the knee, and one on the ankle. The length change of the distances between these points is evaluated together with the recorded sensor data of the Viper system.

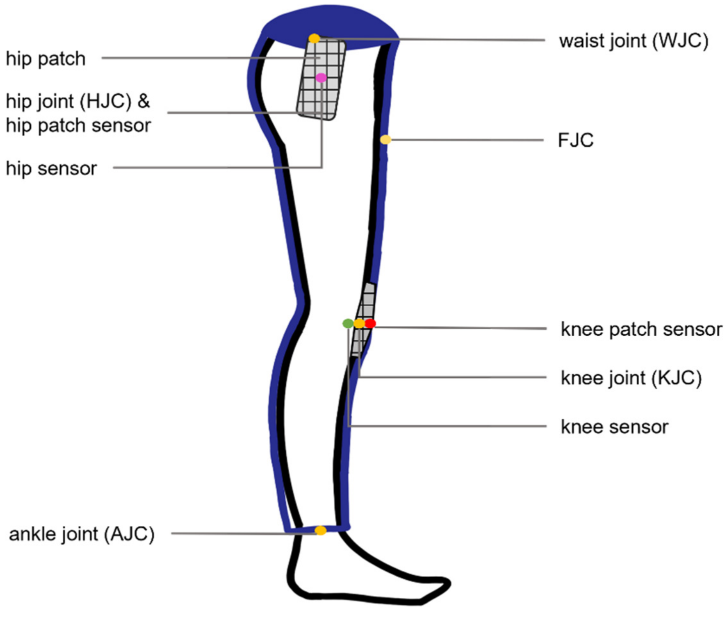

Figure 3: experimental set-up and position of the sensors

The evaluation of the sensor data is carried out in a structured, multi-stage procedure. First, the values generated by the sensor pairs are displayed graphically, with a particular focus on the comparison of these values with the simultaneously acquired scan data, thus enabling a comprehensive assessment of their plausibility. This preliminary analysis is followed by another phase characterized by a systematic calculation of the position differences between the sensors over the entire acquisition session.

The high data acquisition frequency of the Viper System sensors is expected to introduce significant noise. The representation of the absolute values of relative sensor displacements needs to be considered in conjunction with the scan data. To achieve this, it is imperative to smooth the sensor data, and for this purpose, the Savitzky-Golay filter is employed. Moving averages can alter the shape of the data graphs. However, this is not the case with the Savitzky-Golay filter, as it primarily fits low-degree polynomials to the data points within a moving window . The filtered value $\hat{y}(k)$ at the point k is calculated from the sum over the selected window with the size 2n +1. The raw data at the points (k+m) are multiplied by the coefficients, of the selected polynomial (c_m). The coefficients depend on the selected polynomial order and the window size. [12]

$$\hat{y}(k) = \sum_{m=-n}^{n} c_m \cdot y(k+m) \tag{1}$$

Typically, this filter finds application in signal processing and spectral analysis. Applying the filter results in deviations from the raw data, which are quantified using the method of root mean squared error (RMSE).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)$$
$$RMSE = \sqrt{MSE} \tag{2}$$

Given that, for the evaluation with the body scan data of the Move 4D, the data trends are of interest rather than the absolute values, these expected deviations can be tolerated. Nevertheless, for the assessment of maximum sensor displacements, the raw data remains available.

To represent the spatial displacement between the sensors, the Euclidean distance is computed. This distance represents the length of the path between two points in space and is calculated as follows:

$$d(p, \grave{p}) = \sqrt{\sum_{i=1}^{n}(\grave{p}_i - p_i)^2} \tag{3}$$

The time evolution of the calculated position discrepancies, considered together with the simultaneous examination of the scan data, provides insights to identify the precise points along the trajectory where the maximum relative motion between the skin and the fabric of the clothing occurred. This examination framework thus reveals the positions most susceptible to pronounced motion-induced interactions between the human body and the garment.

Results

To illustrate the examination process, Figure 4 shows the results of individual recording sessions for different movements, namely "knee elevation" (A) and "knee rotation" (B). In this context, the pairs of sensors at the knee joint are graphically represented by the green and red traces, while the two blue traces correspond to the sensors in the hip region. Each movement was repeated twice within a single recording session, with the initial points indicated by the black points in the visual representation.

The motion pattern labeled (A) manifests primarily as translational displacement along the Z-axis, as confirmed by the results shown in

Figure *2*. Conversely, the motion pattern (B) effectively captures the complex rotational dynamics underlying the act of raising the knee while rotating it. This observation shows that the sensor configuration used captures the executed motions very well.

It can be inferred that the sensors capture faithfully the nuances inherent in the kinematic actions performed, in compliance with the visual representation and the analytical evaluation.

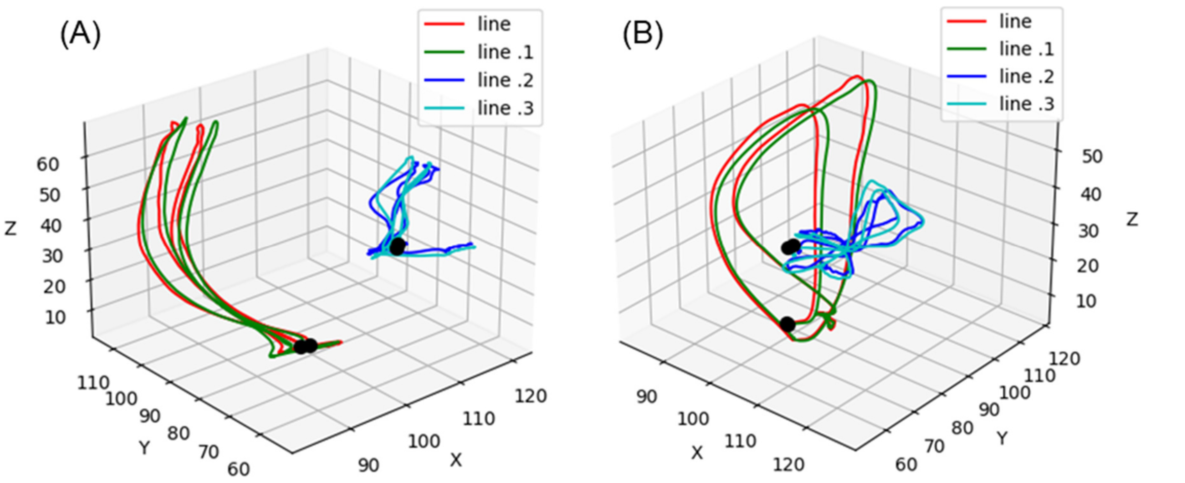

Figure 4: Graphical representation of the sensor measurement data for the movements: knee elevation (A), knee rotation (B)

In Figure 5 the course of the absolute values of the differences between the individual sensor pairs for the movement "lift knee 1" is shown as an example. The graphs each show two peaks resulting from performing the movement twice in one recording session. These data were smoothed using the Savitzky-Golay filter with a second degree polynomial and a window size of 50 data points. The third graph in Figure 5 shows the difference between smoothed and unfiltered data.

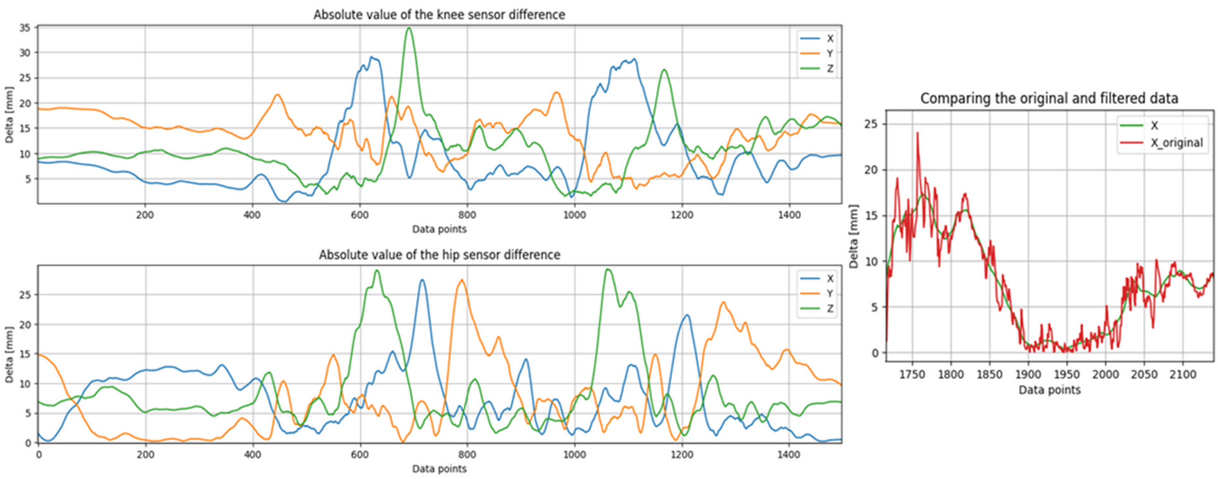

Figure 5: Exemplary evaluation of the data for the movement "Knee lift 1"

The absolute values of the difference of the sensor readings for knee and hip sensors are maximum in z-direction for the movement "lift knee 1". This is identical with the findings from Figure 4. The maxima are between 25 and 35mm. Since the movements were carried out twice in one recording session, there are two maxima. The maxima associated with the graphs demonstrate that in cases where only the knee is elevated, the absolute displacement of the knee sensors in the z-direction reaches its maximum extent. Analyzing the displacements of the hip sensors presents a more intricate challenge due to their involvement in conjunction with shifting body masses, resulting in a complex multidimensional displacement profile. The highest recorded maximum displacement measures 43.1 mm and is achieved in the y-direction during knee rotation. It's worth noting that the measurements' accuracy, as computed through the Root Mean Square Error (RMSE), amounts to 1.89 mm. This indicates the precision and reliability of our measurement methodology.

The analysis of the depicted movements reveals that the displacement of protective elements cannot be adequately described by a single coordinate. The "knee lift" motion is predominantly characterized by vertical movement in the z-direction. However, as the knee is angled, surface curvature increases, leading to the initiation of slippage of the protective element. This behavior cannot be accurately captured by solely considering the z-axis.

Therefore, the Euclidean distance is employed to calculate displacement. The resulting graph is shown in Figure 6, illustrating both movements. The absolute maximum displacement of the knee sensors measures 40.1 mm and occurs during the initial execution of the motion. This peak consistently aligns with the maximum sensor distance observed in the z-direction.

The plateau observed at data point 600 primarily arises from the maximum displacement in the x-direction. This is due to the slight twisting of the knee that occurs unintentionally during elevation, resulting in lateral displacement. This intricate analysis underscores the multidimensional nature of protective element displacement, which is critical for a comprehensive understanding of movement dynamics and the design of effective protective gear.

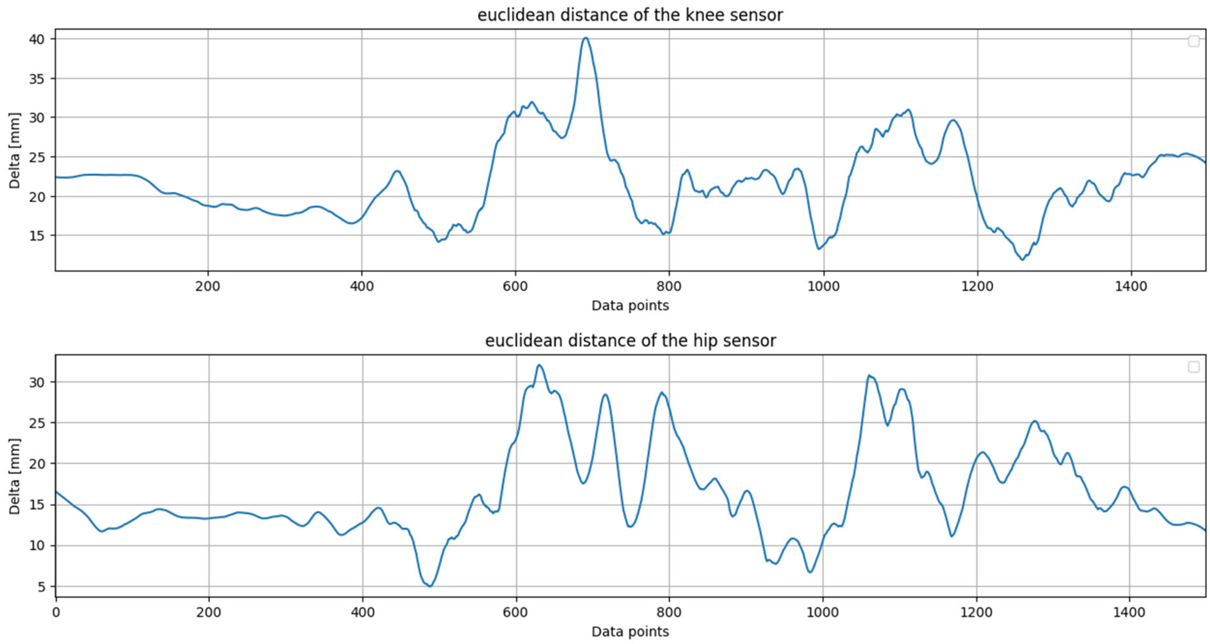

Figure 6: euclidean distance for the motion "knee lift 1"

The maxima for all recording sessions are presented in table 1. The knee rotation motion overlays numerous direction-dependent peaks, making it challenging to evaluate in relation to body position. Consequently, these maxima are represented as ranges.

table 1: maxima of the eucledian distance in all motion recordings

	knee sensor displacement [mm]		hip sensor displacement [mm]	
knee lift 1	47.6	38.0	39.6	39.4
knee lift 2	47.75	41.0	52.7	43.6
knee rotation1	34.5	30.7	57.6	51.4
knee rotation 2	28.6	30.3	46.7	39.0

These data represent the absolute displacement between the sensor on the skin and the sensor on the clothing. This displacement can be understood as a combination of the deformation of body parts while moving, relative movement between skin surface and clothing tissue, the elastic behavior of the material. In order to make statements about the size of protective elements on clothing, the relative movement between clothing and skin must be known.

To understand the dynamics of changes in the surface of the human body during the movement, we used the latest 4D scanning technique. The row scans generated by Move4D scanner are an aligned cloud of points captured by each module. The processing tools included in the Move4D software enable the automatic generation of a 3D mesh that includes 50,000 vertex with homologous correspondence along the sequence of scans.This homology preserves anatomic correspondence within a subject sequence of scans and between subjects. This property allows us to track the displacement of selected points located on the surface of a homologous mesh within a given series of movements.

To simplify the data processing, on Institute of Textile Machinery and High Performance Material the TU Dresden was developed a Matlab workflow to automatically estimation the distances between selected points within each frame based on the mesh vertex IDS data. Using this program, we calculated the changes in the distances of the leg surface measurements during selected typical movements.

An example of plotted diagrams illustrating the distance between specified points (Figure 3) during the movement is shown below.

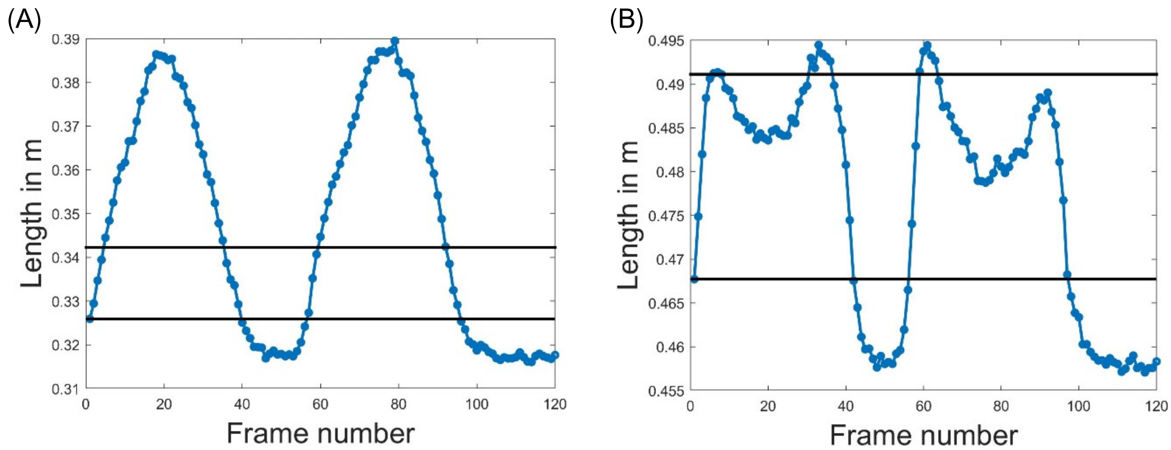

Figure 6: Dynamics of changes in the length of upper leg FJC-KJC (A) and lower leg KJC-AJC (B) during the motion "knee lift 1"

The maximum values of length increases are shown in the table below. The data obtained correlate with the values of sensor displacement during movement (table 1), but are slightly higher. This can be explained by the following: a certain proportion of the leg length increases is compensated for by elongation of the material under the influence of the applied force resulting from the difference in length between the leg surface and the corresponding part of the garment. The value of this elongation depends, on the one hand, on the elastic properties of the material, and on the other hand, on the design parameters of the garment, such as the easy allowances, the location and types of seams, and model features.

In the future, this methodology will be employed to jointly analyze sensor and scan data. The synchronization of software interfaces is still pending. The estimation of the motion of the protective element in the three-dimensional space is a complex task, as the translational-rotational character of the motion is complicated by the deformation of the element according to the changing configuration of the leg in motion.

Consequently, a subjective approach was adopted for the evaluation of scan data. To draw conclusions regarding the overall behavior of protective elements, the recorded motions are meticulously assessed frame by frame, as depicted in Figure Figure 7. This granular analysis ensures a comprehensive understanding of the dynamic behavior of the protective gear.

The representation illustrates that elevating the knee results in the patch shifting in the direction of the inner thigh. This displacement aligns consistently with the maxima observed in the absolute differences of sensor measurements, as shown in the figure 5. The comprehensive behavior of the protective element could not be captured solely through sensor data, necessitating an additional subjective analysis. This multifaceted approach ensures a thorough understanding of the protective gear's overall performance.

*Figure 7: Frame-wise representation of the movement "Knee lift 1: Frame 0 (**A**); Frame 5 (**B**); Frame 10 (**C**); Frame 20 (**C**)*

Discussion

Within the scope of the investigations presented here, it has been demonstrated that the relative motion between the body and clothing during wear can be effectively captured using the combined capabilities of the Move4D and Viper systems.

The insights gained from this study hold significant implications for the design of personal protective equipment (PPE) within the realm of sports. These findings can serve as a foundation for the development of construction guidelines, ensuring that protective gear maintains its efficacy in the event of an athlete's fall, thus minimizing the risk of injuries. Furthermore, the methodology developed here can be leveraged in future research endeavors to address various textile-related inquiries, thereby enabling the accurate representation of the relative motion between the skin and fabric in a wide array of clothing-related scenarios.

This research paves the way for advancements not only in sports equipment but also in the broader field of textile technology and ergonomic design. It provides a robust framework for enhancing the performance and safety of athletes and individuals in diverse applications.

In future research endeavors, it is fundamentally essential to establish synchronization between the Move4D and Viper systems. This synchronization stands as a pivotal prerequisite, as it would enable the nuanced tailoring of construction guidelines in response to specific directional considerations within the ambit of these investigations. Furthermore, the integration of this synchronization mechanism would, in addition, unlock the potential for the comprehensive assessment of intricate anatomical regions, notably including but not limited to the hip region. This multifaceted enhancement in system coordination holds significant promise for advancing the precision and versatility of our investigative methodologies.

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