Development of an animated 3D avatar for dynamic fit analysis of protective clothing

Tena Risek, Slavenka Petrak, Maja Mahnić Naglić*
University of Zagreb Faculty of Textile Technology, Zagreb, Croatia
*Corresponding author: maja.mahnic@ttf.unizg.hr

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Original scientific paper**

The paper presents the development of an animated 3D avatar for the digital prototype dynamic fit analysis of a fire protection uniform. Dynamic fit analysis involves testing clothing on the body in motion, where the range of motion in which testing is performed depends on the type and purpose of the garment. CAD systems for the development of digital 3D prototypes of clothing allow the analysis of dynamic fit on animated avatars, but the availability of avatars that enable the animation of specific movements is still very limited. It is also one of the most prominent obstacles to the wider application of digital prototyping in the process of developing new clothing models with high functional requirements. As part of the research, a methodology for the development of an avatar adapted to a scanned 3D model of the target subject and the animation of specific movements, relevant for the examination of the protective uniform, determined by the analysis of the movement kinematics of the HGSS employees in intervention situations based on video recordings was set. The development process integrates 3D body scanning, 3D animation applications, and kinematics databases of various movements into a CAD system for developing digital prototypes. This achieves very good results from the aspect of anthropometric adjustment of avatars, and the process of animation of targeted movements is significantly simplified and accelerated for the end user, which greatly contributes to the wider application and possibilities of analyzing digital clothing prototypes in dynamic conditions.

Keywords: *avatar; 3D animation; protective clothing; dynamic fit*

Izvorni znanstveni rad**

Razvoj animiranog 3D avatara za analizu dinamičke pristalosti zaštitne odjeće

U radu je prikazan razvoj animiranog 3D avatara za analizu dinamičke pristalosti digitalnog prototipa uniforme za zaštitu od požara. Analiza dinamičke pristalosti podrazumijeva ispitivanje odjeće na tijelu u pokretu, pri čemu raspon pokreta u kojima se provodi ispitivanje ovise o vrsti i namjeni odjevnog predmeta. CAD sustavi za razvoj digitalnih 3D prototipova odjeće, omogućuju analizu dinamičke pristalosti na animiranim avatarima, ali je dostupnost avatara koji omogućavaju animaciju specifičnih pokreta još uvijek vrlo ograničena. To je ujedno i jedna od istaknutijih prepreka široj primjeni digitalnog prototipiranja u procesu razvoja novih modela odjeće s visokim funkcionalnim zahtjevima. U okviru istraživanja postavljena je metodologija za razvoj avatara, prilagođenog skeniranom 3D modelu ciljanog ispitanika i animaciju specifičnih pokreta, relevantnih za ispitivanje zaštitne uniforme, utvrđenih analizom kinematike pokreta djelatnika službe HGSS-a u interventnim situacijama na temelju video snimki. Razvojni proces po segmentima integrira 3D skeniranje tijela, aplikacije za 3D animaciju i baze podataka o kinematici različitih pokreta u CAD sustav za razvoj digitalnih prototipova. Time se ostvaruju vrlo dobri rezultati s aspekta antropometrijske prilagodbe avatara, a postupak animacije ciljanih pokreta se za krajnjeg korisnika značajno pojednostavljuje i ubrzava, što uvelike doprinosi široj primjeni i mogućnostima analize digitalnih prototipova odjeće u dinamičkim uvjetima.

Ključne riječi: *avatar, 3D animacija; zaštitna odjeća; dinamička pristalost*

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1. Introduction

Computer 3D body models are used in various areas of research and development and, depending on the purpose, must meet the required level of realism, geometry complexity and functionality in terms of the ability to adjust the dimensions and/or animation of the body model. The human body is an extremely complex system, and achieving realism in modelling and animation of digital human models is an extremely complex task and represents one of the main limitations to the wider application of animated avatars in various areas, where ergonomically designed products whose functionality depends on adjustment to the human body are developed. In the field of computer design and development of digital 3D clothing prototypes, high demands are required, in terms of adjustment of a computer body models to the the targeted anthropometric characteristics and body dimensions, since in 3D simulation the computer analysis of a garment in dynamic conditions, i.e. on a body in motion, is based on the contact mechanics between the body and the simulated garment, where the behavior and deformability of the garment are determined by defined parameters of the textile material physical and mechanical properties [1-5]. The clothing fit to the body under dynamic conditions is one of the most attractive topics in the field of clothing engineering. Dynamic fit directly affects the functionality of the garment, as one of the most important elements in the process of designing protective clothing. The human body in motion deforms in terms of changes in surface dimensions, which requires additional adjustment of the corresponding parts of the garment, in order to avoid restriction of movement, or discomfort for the user due to poor fit [6-8]. By simulating a garment model on an animated body model, it is possible to analyze the deformation of the digital garment prototype geometry in contact with the body and assess functionality in targeted movements, before creating actual model samples, which from a sustainability perspective represents significant savings in time, material and financial resources, and a reduction in production waste, compared to the traditional development and testing of a larger number of physical samples.

In CAD systems for digital clothing design, parametric body models that allow the adjustment of body dimensions are most often available, either by interactively entering the values of individual body measurements, which is a rather complex and time-consuming process with a limitation in terms of insufficiently precise adjustment to the body shape and posture, or by direct entry and overlapping with the body model obtained by 3D scanning, whereby it is necessary to pay attention to the compatibility of the subject's body position during scanning, additional processing of scanned models in terms of closing surfaces in shaded areas, compatibility of the local coordinate system within the 3D object, and conversion of the model into a recording format and measurement units supported by the particular CAD system [9,10]. However, such models usually do not allow motion or the animation capabilities are limited to standard movements such as human gait, usually a mannequin gait for the purpose of presenting models in the form of virtual fashion shows, or simpler movements of the upper and lower extremities that most often do not meet the requirements of testing protective clothing in targeted, specific motion. For this aim, animated avatars are developed depending on the purpose of the clothing item, which requires good knowledge and application of mathematical operations in computer graphics and a high level of skill in 3D modeling and animation of objects [11-14].

Animation (lat. *animatio* = bring to life) is defined as the rapid display of two-dimensional images or three-dimensional objects with the aim of obtaining the illusion of movement, which occurs due to the eye inertia, whereby the impression of the image we see remains on the retina of the eye for approximately 1/25 of a second [11]. The intensive development of animation began in the 19th century with the development of the movie industry, while with the computer technology development, animation found its application in broader areas such as medicine and engineering, but it is most represented in creative industries such as the movie and gaming industries. Computer 3D animation is the digital successor to the traditional animation technique in which digital 3D models are used for animation. 3D animation involves a series of methods and techniques by which objects in a scene move and/or deform. Movement includes translations and rotations of objects, while deformation is considered to be the modification of the shape of a 3D object, by moving the vertices of a polygonal mesh that defines its surface. Computer models of bodies for animation differ in their complexity, depending on the application. From the first animated models developed in the 1970s, which were based on simple geometric primitives, todays layered models are built from an internal skeleton that defines movement and an external surface layer which defines the body shape [11,12]. The internal kinematic skeleton represents an abstract mathematical model for controlling the body, built of stick, rigid segments connected by flexible joints, whose movements are defined as a set of hierarchically connected transformations controlled by the positions of the joints, and they differ in the

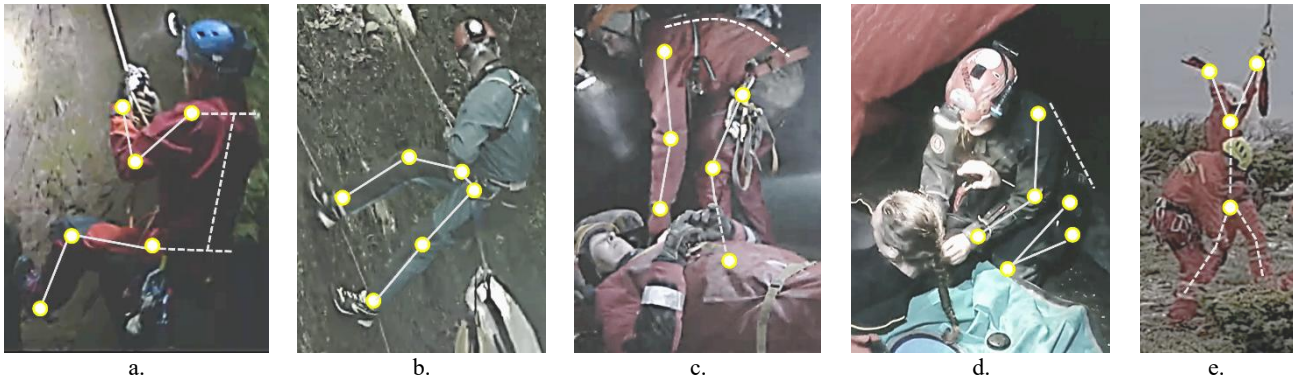
number of rigid segments and joints, and in the degrees of freedom of the joint movement [15,16]. The internal skeleton is created using the rigging technique, which determines the level of mobility of the model and the possibilities of the animation itself. The external surface model represents the surface layer of the skin of the body, whose movements and deformation are conditioned by the movements of the internal skeleton. Connecting the internal skeleton to the surface model is called the skinning technique, and it involves defining the influence of the displacement of the internal skeleton on the movement and deformation of the surface model via weight coefficients [11]. Each bone has a defined weight coefficient in relation to each surface model polygon vertex that it moves, and the final position of each vertex is the sum of the displacement values of all bones that affect the displacement of that vertex, multiplied by the weight coefficient of the influence of the displacement of the corresponding bone. In addition, various algorithms are applied to approx. the physical parameters of the interaction of multiple anatomical layers, most often the muscle layer, and to map deformations into a single deformable surface model [11,16,17]. Today, various plug-ins applicable to CAD programs for 3D animation can be found in commercial use, such as Autodesk Maya or Motion Builder, which more or less realistically approximate muscle deformations, and by properly selecting methods and techniques in the development of an animated body model, a satisfactory level of deformation realism can be achieved, depending on the body model purpose and use.

In addition to the type of digital 3D model for animation, the animation technique itself is also very important. The most commonly used animation technique is the key-frame technique, which is a digital version of classic cartoon animation. It is based on placing a digital 3D model of the body in key positions on the timeline, with parameter interpolation performed in the intermediate steps and generating a complete animation. Each frame indicates the movement of the object in a certain period of time, therefore the distance between the key positions defines the speed of the body movement, or animation, and the number of key positions on the timeline depends on the complexity of the animation. The method requires a good knowledge of the biomechanics of human body movement and a high level of 3D animation skills, since linear interpolation is performed between the defined key positions, which easily leads to unnatural intermediate positions and mechanical movements. Given the difficulties presented, motion data recorded using Motion Capture (MoCap) systems are often used for animation, which contain parameters of natural movement dynamics and can be transferred to a computer 3D body model. The complex additional processing of MoCap data as well as the high cost of such systems greatly limit the application of this method mainly to the movie and gaming industries [11,12,18].

2. Experimental

2.1. Motion analysis of the mountain rescue service workers (HGSS) in emergency situations and definition of characteristic movements for testing the dynamic fit of clothing

Due to the specific working conditions of HGSS employees and the need to perform precise and physically demanding procedures, it is very important to identify specific movements in intervention situations. This ensures a better understanding of the needs of employees and enables more efficient design and development of functional uniforms, while respecting the current relevant standards for protective clothing [19-22]. For this purpose, based on publicly available videos of actual interventions by HGSS employees, a movement analysis was conducted, identifying characteristic and repetitive body movements (Fig.1), or groups of movements relevant



a. b. c. d. e.

Fig.1 Analysis of movement kinematics using video recordings of emergency actions of HGSS employees: a. rope climbing, b. rope descent, c. lifting and carrying a stretcher, d. providing first aid, e. signalling to the helicopter [23,24]

Tab.1 Groups of specific movements determined by analyzing video recordings of HGSS intervention actions

First group of movements - Climbing and descending on a rope, Fig.1a and 1b [23]
Climbing - Simultaneous upward movements of the arms, with the palms reaching and grasping the peg on the rope. By pulling the peg downwards, the arms bend at the elbow joints and the hands are brought closer to the chest area, while pushing the legs away from the vertical surface and alternately bending and extending the hips and knees, the body is raised to a higher level. Descending - The body is slightly tilted back to maintain balance. One hand is held on the peg, while the other is controlling rope release, with both arms bent at the elbows. The legs are supported on a vertical surface and alternately bent and extended at the hip and knee joints. - Repetitive, synchronized movements of the arms and legs, pronounced bending and stretching in the shoulder, elbow, hip and knee joints.
Second group of movements - Providing first aid, Fig.1c [23]
- From an upright body position, a lunge is performed with one leg while simultaneously bending the knee and gradually lowering the knee of the other leg to the ground, after which the knee of the first leg is also transferred to the ground and the body remains in a kneeling position. - The torso leans forward by bending at the hips, with the pelvis lowering towards the calves, which leads to additional bending of the legs at the knees. - The torso is rotated to the left and right as needed, while the arms perform various movements from the shoulders and elbows, such as reaching, carrying, and releasing. - The movements highlight the need for functionally designed protective uniform in the knee, hip, torso and arm areas to provide comfort for flexibility of movement.
Third group of movements - Lifting and carrying a stretcher with an injured person, Fig.1d [23]
- From an upright body position, the torso leans forward and, with the legs slightly bent at the knees, assumes a semi-squat position. - From a semi-crouching position, the stretcher is grasped with one hand, after which the body position returns to an upright position, while simultaneously lifting the stretcher. - The free hand is placed at an angle of approximately 45° to maintain the balance.
Fourth group of movements - Crossing obstacles such as tree trunks and rocks [23]
- Bending both legs at the knee joints, with one leg being lifted, thrown over the obstacle and lowered to the ground on the other side, followed by the same movement with the opposite leg. - Pronounced bending and mobility in the hip and knee joints.
Fifth group of movements - Signalization and communication with the helicopter, Fig.1e [24]
- From an upright standing position, the arms are raised above the head, forming a "Y" shape, which requires freedom of movement in the shoulder and upper arm area and a good clothing fit, especially in conditions of strong air currents. - As the helicopter approaches, the body lowers to the ground in a half-kneeling or crouching position to maintain stability.

for testing the functionality of HGSS protective uniform in dynamic conditions [23,24]. Five groups of specific movements were selected, which include an increased load on certain parts of the body and which could potentially cause increased stress and deformation of protective uniform in certain areas, Table 1. Based on the analysis, a set of eight specific body positions was defined for further research and development of digital avatar animations.

2.2. 3D body scanning of test subject in defined characteristic body positions

Using the VITUS Smart 3D body scanner and ScanWorx V2.7.2 and Anthroscan software packages from Humanetics, the male test subject was scanned in an upright standing position, and based on the determined body measurements, the parametric 3D model was adjusted according to the individual anthropometric characteristics of the test subject. Additional scanning was performed in eight defined characteristic positions, with the purpose of controlling and comparing the final positions of the digital body model in the animation development process.

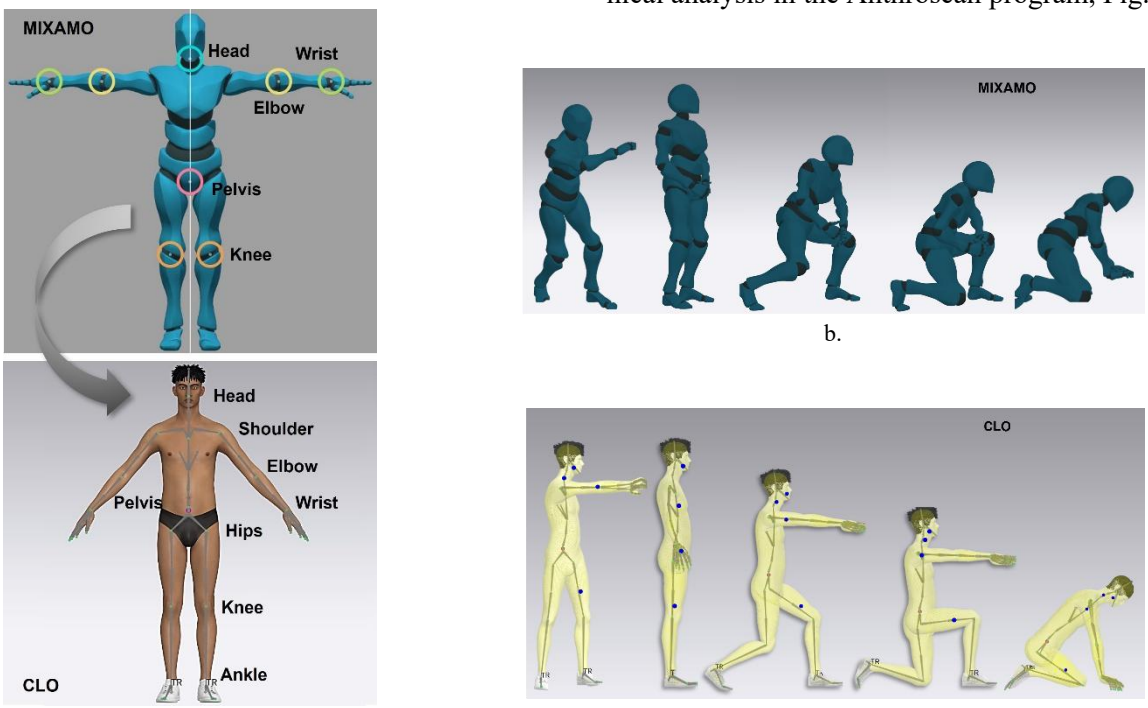
2.3. Avatar animation in a defined set of movements

For the avatar animation, data on the kinematics of movements available in the Mixamo platform database were used. Mixamo is an Adobe application, which enables automatic rigging techniques and the application of predefined animations to 3D body models. The application uses algorithms for recognizing the morphology of the human body, based on which an internal hierarchical model of the skeleton is generated and a skinning technique for connecting

the kinematics of internal joints with the surface model is applied. The application provides a large database of kinematics of various movements in fbx file format, which can be further customized in various CAD programs for 3D animation [25]. In this sense, movements that most closely match a set of previously defined movements and body positions relevant for testing protective clothing were selected from the Mixamo database, Fig.2b.

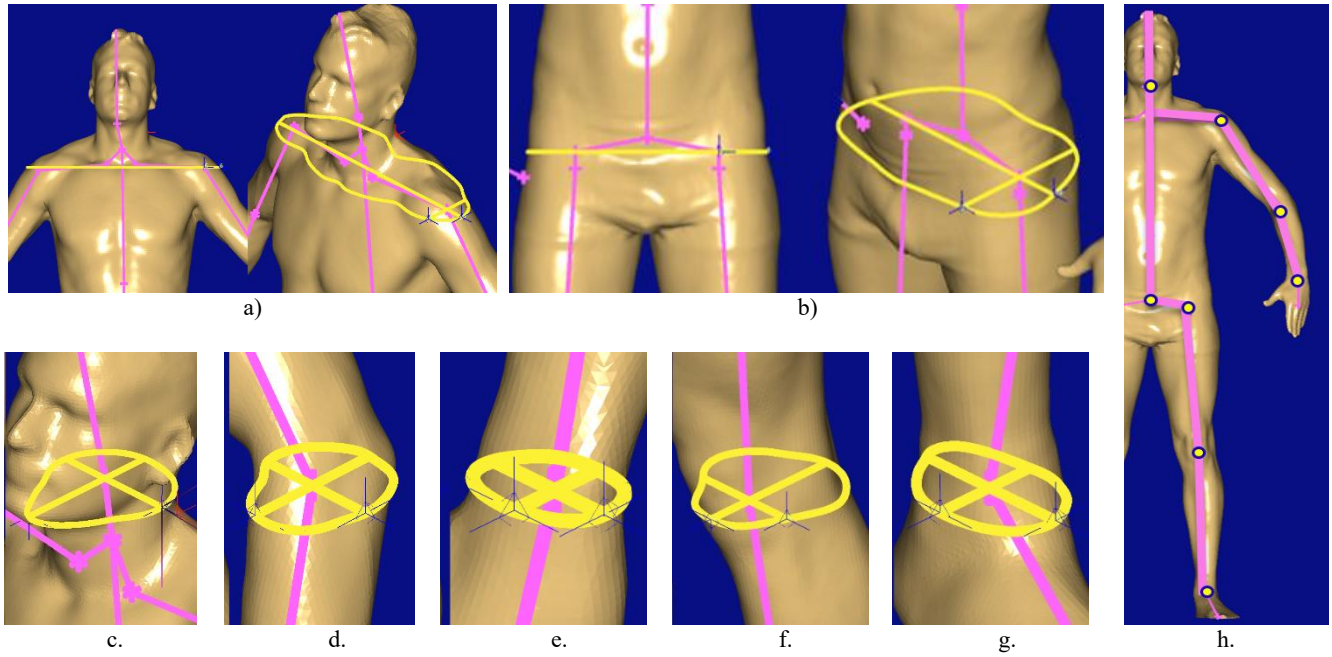
Data on each movement were loaded into the CLO program for computer clothing design, and applied to the 3D avatar [26].

The hierarchical structure of the kinematic model generated by the Mixamo algorithm was initially analyzed in relation to the hierarchy of the kinematic internal skeleton of the parametric body model from CLO, Fig.3a. Based on the 3D scanned body model and the application of the algorithm for biomechanical analysis in the Anthroscan program, Fig.3, the



a. b. c.

Fig.2 Animation development: a. analysis of the Mixamo and CLO model kinematic hierarchy structure, b. animation and different body positions from the Mixamo database, c. adjusted avatar's final body positions in the CLO program



a) b) c. d. e. f. g. h.

Fig.3 Analysis and determination of the internal skeleton joint points coordinates on the scanned 3D body model: a. shoulders, b. hips, c. head/neck, d. elbow, e. wrist, f. knee, g. ankle, h. hierarchical structure of the internal skeleton

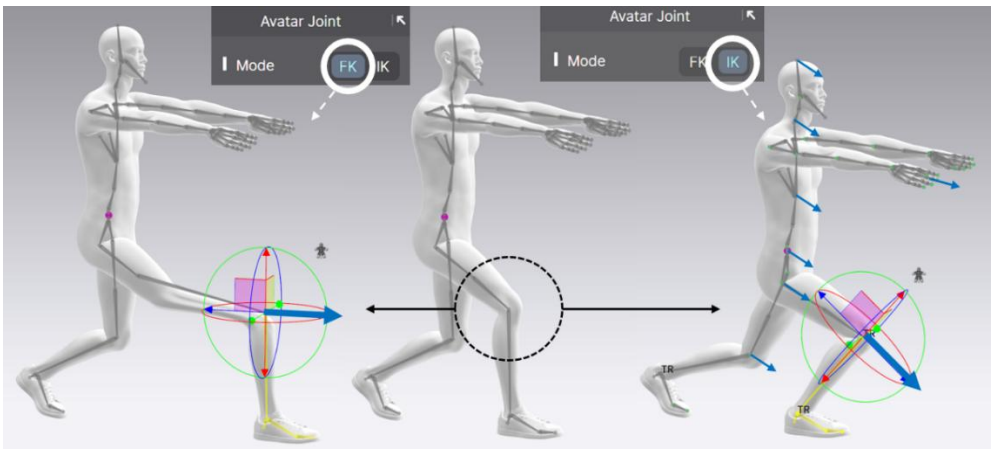
Tab.2 Joint coordinate displacements relative to the origin of the hierarchical structure of the internal skeleton defined according to the scanned 3D body model

Initial position P0	Coordinate displacements relative to the origin (pelvis) [m]			Position P6, Fig.3f	Coordinate displacements relative to the origin (pelvis) [m]		
Joint	x	y	z	Joint	x	y	z
Pelvis / origin	0	0	0	Pelvis / origin	0	0	0
Head / neck	0,582	0,018	0,001	Head / neck	0,582	0,018	0,001
Shoulder L	0,539	0,003	0,201	Shoulder L	0,539	0,003	0,201
Elbow L	0,284	-0,014	0,372	Elbow L	0,539	0,231	0,201
Wrist L	0,075	0,093	0,424	Wrist L	0,539	0,440	0,201
Hips L	-0,020	0,000	0,107	Hips L	-0,020	0,000	0,107
Knee L	-0,458	0,001	0,134	Knee L	-0,020	0,459	0,134
Ankle L	-0,878	-0,055	0,155	Ankle L	-0,420	0,459	0,155

hierarchical structure of the internal skeleton was analyzed and the coordinates of each joint in the initial position were determined. Based on determined coordinates the interactive displacements were calculated and defined for additional adjustment of the end joint positions in order to obtain the animation of the defined movements of the customized avatar in the CLO program, using the Avatar (Joint) Editor and Animation Editor functions, Fig.2c.

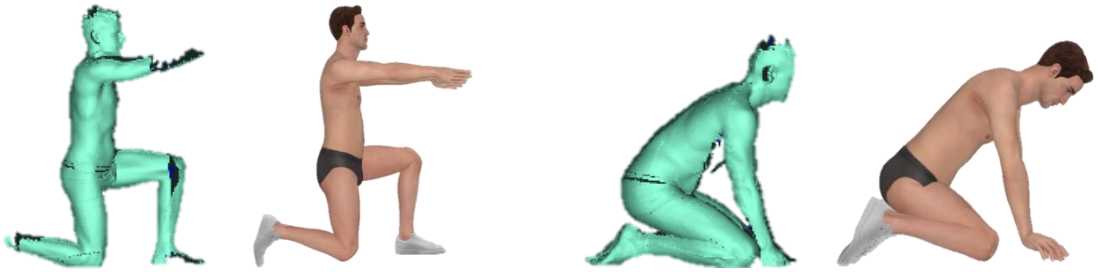
When adjusting the joint positions in the CLO program, the inverse kinematics method was applied, which connects the hierarchical structure in such a way that, based on the set position of the end joint, it hierarchically adjusts the position of all connected segments, Fig.4b. Unlike direct kinematics, in which individual joint displacements are independent of the hierarchical structure and it is necessary to adjust each individual joint, which is extremely time-consuming and leads to unnatural deformations of the surface model geometry (Fig.4a) inverse kinematics ensures hierarchical continuity of geometry displacements, which results in a high level of realism of the surface model, and prevents displacements that lead to unrealistic positions and deformations [11,12,26].

Joint position control was performed by comparing the customized avatar with scanned 3D models of the subjects in defined positions, Fig.5.



a. b.

Fig.4 Methods of kinematic skeleton joints positions adjustment: a. direct kinematics, b. inverse kinematics



a. b.

Fig.5 Comparative analysis of scanned 3D models in defined positions and adjusted avatar: a. position P6, b. position P8

3. Results

Using the proposed methodology, an animated 3D avatar adjusted to the target test subject was developed, which allows the performance of specific movements, relevant for testing the functionality of HGSS protective uniform in dynamic conditions. By integrating data obtained from 3D body scanning and a parametric body model, a high level of compliance of the avatar geometry with the individual body measurements of the subjects was achieved. Analysis of the kinematic structure and adjustment of joint positions resulted in animations that reproduce defined characteristic body positions, Fig.6, while maintaining the continuity of movement and functional stability of the model within the CAD system.

The research results confirm that the use of predefined animation data, with additional adaptation of the kinematic skeleton, based on the biomechanical analysis of the scanned 3D model of the target subject's body, enables efficient and time-reduced development of animations, compared to traditional manual animation techniques, without significantly compromising the level of realism required for the dynamic fit analysis of the digital clothing prototypes. The developed avatar was successfully implemented in the process of computer 3D simulation of a protective uniform digital prototype, enabling the analysis of garment deformations and the identify-cation of critical zones of increased stress in targeted movements, Fig.7.

5. Conclusion

In the presented research, a methodology for the development of an animated 3D avatar adjusted to the individual anthropometric characteristics of the scanned test subject was developed and evaluated, with the aim of analyzing the dynamic fit of a protective uniform of the Croatian Mountain Rescue Service digital prototype. The research is aimed at overcoming the limitations of existing CAD systems for clothing design, especially in terms of the availability of anthropometrically adjustable avatars

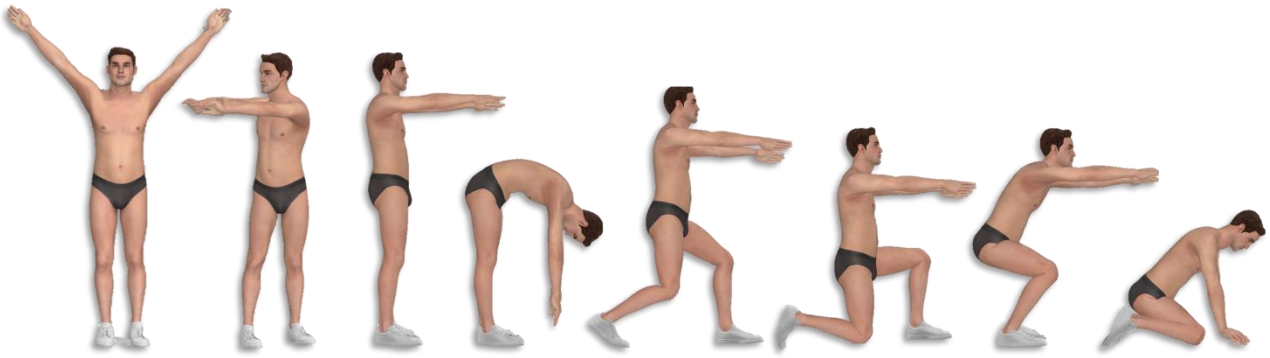


Fig.6 Animated avatar in eight characteristic body positions: a. P1 - "Y" arm extension, b. P2 - torso rotation, c. P3 - forward arm extension, d. P4 - forward bend, e. P5 - lunge with knee bend, f. P6 - kneeling with lunge, g. P7 - squat, h. P8 - kneeling with forward torso tilt

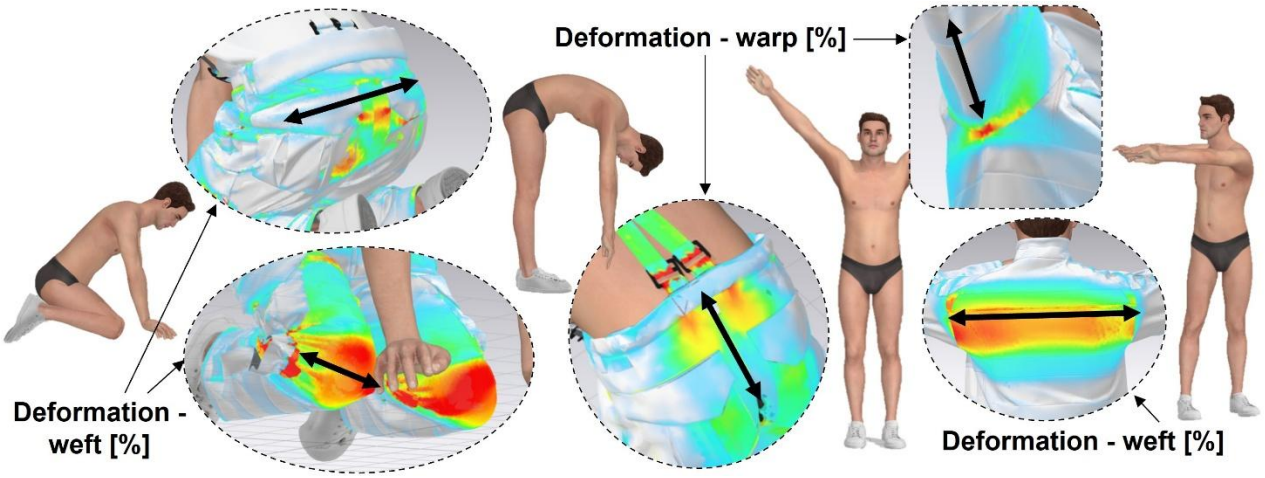


Fig.7 Deformation analysis of the HGSS protective uniform digital prototype in dynamic movement conditions

with the ability to perform specific movements. The conducted analysis of the kinematics of HGSS employees intervention activities identified characteristic movements relevant for testing the functionality of protective clothing in dynamic conditions. Based on the defined methodology, the procedures of 3D body scanning, adjustment of the parametric model to individual body measurements, and application of predefined animation data were integrated, with additional adaptation of the kinematic structure within the CAD system. Such an approach enabled the generation of animations that sufficiently reproduce the real dynamics of movement, while maintaining control over the final positions of the body. Research proved a functional and time-efficient solution for the development of animations that significantly contributes to the wider application of digital prototyping in the development of protective clothing with high functional requirements.

The research results show that the proposed methodology provides a high level of geometric adjustment of the avatar and enables efficient analysis of deformations and behavior of a digital garment prototype in contact with a moving body. This creates a reliable basis for assessing the functionality of protective clothing in the early stages of product development, before the creation of physical prototypes. Analysis of digital garment prototypes on an animated body model provides insight into garment deformations, potential areas of movement restrictions and reduced comfort, which significantly contributes to the optimization of design solutions in accordance with functional requirements and the sustainability of the development process, by reducing the material and financial resources required to create a larger number of physical prototypes.

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