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19 June 2026

FEATURE ARTICLE

A Semi-Automated Pipeline for the Creation of Virtual Fitting Room Experiences Featuring Motion Capture and Cloth Simulation

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Abstract—Technological advancements are prompting the digitization of many industries, including fashion. Many brands are exploring ways to enhance customers' experience, e.g., offering new shopping-oriented services like Virtual Fitting Rooms (VFRs). However, there are still challenges that prevent customers from effectively using these tools for trying on digital garments. Challenges are associated with difficulties in obtaining high-fidelity reconstructions of body shapes and providing realistic visualizations of animated clothes following real-time customers' movements. This paper tackles such lacks by proposing a semi-automated pipeline supporting the creation of VFR experiences by exploiting state-of-the-art techniques for the accurate description and reconstruction of customers' 3D avatars, motion capture-based animation, as well as realistic garment design and simulation. A user study in which the resulting VFR experience was compared with those created with two existing tools showed the benefits of the devised solution in terms of usability, embodiment, model accuracy, perceived value, adoption and purchase intention.

Fashion is one of the most significant manufacturing industries at the global level. According to the latest statistics, it generated a market value of 821 billion US dollars in 2023 and is forecast to reach even greater values in the next years [1].

Like other industries, fashion is largely impacted by advancements in technology [2]. In particular, a key role is played by Computer Graphics (CG), which enables the digital transformation of traditional design processes through the creation of virtual fashion assets [3]. CAD tools for the fashion industry like, e.g., Marvelous Designer[1] and CLO3D[2], can be used to simulate the behavior of clothes on pre-animated avatars, further empowering the design steps. These tools also provide export routines to use the generated digital assets into different platforms or game engines such as Unity[3] or Unreal Engine[4]; in this way, applications directly accessible to the customer can be created.

Over the last decade, and specifically in the last few years with the COVID-19 pandemic, the fashion industry witnessed an explosion of e-commerce, and CG was regarded as a way to develop new solutions potentially capable of improving the shopping experience. Moreover, social and environmental concerns started to prompt new attempts to promote sustainable consumption by integrating virtual assets into existing processes [4].

One way adopted by the fashion industry to tackle the above needs is through the development of Virtual Fitting Room (VFR) experiences and Virtual Try On (VTON) applications [5]. VFRs aim to replicate a physical experience by providing detailed feedback on how clothing fits. For this reason, they usually rely on high-fidelity 3D reconstructions of the customer's body. Other technologies, e.g., related to Internet of Things

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[1]Marvelous Designer: https://www.marvelousdesigner.com/
[2]CLO3D: https://www.clo3d.com/en/
[3]Unity: https://unity.com/
[4]Unreal Engine: https://www.unrealengine.com

(IoT), can be integrated to improve user engagement and personalization of VFRs by leveraging data collected in real time [6].

VTON, in turn, is a broad term that encompasses technologies focusing on the appearance and visual aesthetics of products. In this case, virtual items are generally overlaid on real-time images or videos. Differently than VFRs, VTON applications are tailored to many product categories, including clothing but also accessories, makeup, and home decor.

Various companies started exploring VFRs and VTON applications, integrating them into online shops or within in-store, assisted shopping experiences. Examples are the technologies used by brands like Ray-Ban[5] and Gucci[6], the tools developed by Vyking[7] for Zara, Adidas, Timberland, and Crocs, or the solutions proposed by ZERO10[8] for Tommy Hilfiger, Coach, Nike, and Vogue, to name a few.

Studies in the literature showed that VFRs and VTON applications, often empowered with Augmented Reality (AR) technology and AI-based services for size or garment recommendation, can influence the customers' intention to make a purchase and provide highly personalized shopping experience able to maximize satisfaction [7], especially when customized digital avatars are envisioned [8]. Moreover, they are able to significantly accelerate the process of deciding what to wear, by also reducing returns and wastes [5], [9].

In this paper, the attention was focused on current challenges faced in the design and development of VFRs. Although VFRs have been technically available for a while, this technology is still not particularly widespread. One of the reasons is represented by customers' potential concerns regarding the accuracy of the simulation [5]. Analyzing the scientific literature and the solutions already available in the market, it is possible to note that VFRs typically feature the following characteristics: i) 3D personalized avatars based on body measurements/scanning, ii) real-time animations of the avatars generated by tracking the customer's movements, iii) the availability of a digital catalog iv) fabric simulation.

In order to address the mentioned concerns, it is necessary to develop VFRs featuring high-quality simulations that can accurately reconstruct the 3D body of the customers, track their movements, and simulate clothes in real time. Several alternatives have been proposed in the literature, each one with different capabilities or performance [5], but to the best of the authors' knowledge a comprehensive pipeline integrating all these characteristics is currently missing.

Moving from the above considerations, the paper aims to fill this lack by proposing a semi-automated pipeline supporting the whole workflow for the creation of VFR experiences, from avatar generation to cloth simulation with up-to-date technologies. More specifically, the pipeline relies on avatar descriptions based on the Sparse Unified Part-Based Human Representation (SUPR) [10], which is the most recent parametric model for human body description. The pipeline features a tool for the automatic generation of high-fidelity avatars representing the customer's body using AI techniques. Moreover, it offers the possibility to interactively animate the personalized 3D avatar through motion capture. To this aim, tools and libraries are proposed/leveraged to i) automatically reconstruct the data structure needed for animating the avatar, ii) enable the tracking of the customer's movements, and iii) simulate the physics of the clothes. The first feature was made available through a custom Blender addon, which generates animation data structures compliant with the SUPR model.

Customer's movements are captured in real-time through a monocular RGB camera using the Google MediaPipe[9] library. To handle the physics of the clothes' fabrics, Unreal Engine and, in particular, the uDraper plugin[10] were chosen for the quality they can offer in terms of realism and smoothness of the simulation. Finally, the pipeline is meant to be integrated with existing CAD tools (presently CLO3D), which can be exploited for designing the garments to be made available in the VFR experience.

All the mentioned tools and technologies have been enclosed in a unified process. Many of the functionalities provided by each stage of the process have been automated in order to minimize the manual effort required to make changes (e.g., adding a new avatar or garment to the virtual catalogue) to the experience.

RELATED WORKS

VFRs are attracting important investments from fashion brands. A number of commercial solutions already exist, which can be easily integrated in existing

[5]Ray-Ban: https://www.ray-ban.com/uk
[6]Gucci: https://ggshadefinder.gucci.com/
[7]Vyking: https://www.vyking.io/
[8]ZERO10: https://zero10.ar/business
[9]MediaPipe: https://developers.google.com/mediapipe
[10]uDraper: https://udraper.com/

e-commerce platforms. For instance, Sizebay[11] and Boldmetrics[12] are web-based tools that can be used to let customers create 3D representations of their body by asking them to provide some basic measurements (chest, waist, hips, weight, and height). These digital representations are not only leveraged for visualization purposes, i.e., making customers see how certain items fit but also to provide personalized recommendations on the most suitable size to purchase. Other tools like, e.g., Goodstyle.tech[13] request the customers to provide some pictures, which are used to delivered improved recommendations considering also the color of the skin and hair.

Besides creating an avatar for the customer, VFRs also require the generation of realistic and convincing 3D models of the garments. Some examples of tools devoted to garment digitalization are Drapr[14] and ReactiveReality VTON[15]. The generated 3D models can be uploaded on online platforms such as Style.me[16] and Wearfit[17] to see how they fit on standard mannequins. Often these mannequins can be personalized like in the solutions mentioned above, but typically cannot be animated.

The market also offers AR applications like, e.g., WANNA Wear[18], which allow the customers to visualize digital garments overlapped to their body using the camera and display of their mobile devices or into ad hoc, in-store spaces with dedicated equipment (like virtual mirrors). Succesful examples include the experiences offered by brands such as Dolce&Gabbana[19], FARFETCH[20], Diesel[21], Reebok[22], etc.

For what it concerns academic research, over the last few years numerous methods have been explored to support the creation of VFR experiences or, more in general, VTON applications. As a matter of example, the study in [11] investigated whether AR is effective at conveying reliable apparel product information, e.g., fit, size, and product performance. The results of a user study confirmed that this kind of solutions positively influences the attitudes of potential customers toward apparel purchase intentions when shopping online. However, it is worth observing that it is quite common for AR solutions to be characterized by a limited-quality cloth simulation. This is due to several factors, such as the performance limitations imposed by the hardware that is typically used, the possible lack of an accurate 3D model of the customer to which the garment can be fitted during the simulation, and issues related to AR tracking stability.

of 2D images provided by the customer. For instance, the work in [12] presented TryOnGAN, an AI algorithm that generates high-quality syntheses of try-on images. Specifically, given a pair of images showing the target person and a garment on another person, it automatically generates the target person in the given garment, ensuring that original body shape, skin color, and hair are maintained. The algorithm is also able to wrap and blend the garment with the target person and transfer high-frequency details such as geometric patterns and complex textures from the source image to the output. Although this solution can achieve good results in terms of visual appearance of the cloth, only static images can be obtained.

To cope with this limitation, the literature presents alternative solutions that have been mainly designed to provide fashion style tips through interactive experiences. For instance, the system proposed in [13] includes a 55-inch display and a Microsoft Kinect device that is used to track a customer in front of the display, thus enabling natural interactions and the possibility to overlay garments on the customer's image while he or she is moving. More recent examples of this technology are systems like Uniqlo Magic Mirror[23], FXGear FXMirror[24], and YNAP YooxMirror[25], which support interactive experiences in which customers can try on garments with different colors and sizes either on their own body (by overlapping digital contents to real ones) or on personalized avatars created on the fly by choosing some key characteristics from a library. Although these solutions can increase the level of interactivity, they also present limitations in terms of cloth simulation due to the lack of an accurate body model to which the garment has to be wrapped [14].

To overcome the above issue, solutions were proposed in the literature that rely on 3D scans of the customers' body, digital models of the garments, and cloth simulation.

An example is provided in [15], where a Microsoft

11 Sizebay: https://sizebay.com
12 Boldmetrics: https://boldmetrics.com
13 Goodstyle.tech: https://goodstyle.tech/
14 Drapr: https://www.drapr.com/
15 ReactiveReality: https://www.reactivereality.com
16 Style.me: https://style.me
17 Wearfit: https://dev.wearfits.com
18 WANNA Wear: https://wanna.fashion/
19 Dolce&Gabbana: https://wanna.fashion/dolce-gabbana
20 FARFETCH: https://wanna.fashion/farfetchapp
21 Diesel: https://wanna.fashion/diesel
22 Reebok: https://wanna.fashion/reebok
23 Uniqlo Magic Mirror: https://holition.com/work/uniqlo
24 FXGear FXMirror: http://www.fxmirror.net/en/main
25 YNAP YooxMirror: https://www.ynap.com

Kinect was leveraged to track the customer's joints. The tracking data were then used to align the 3D models of the clothes with that of the customer as well as to handle hand gestures for scrolling the list of available clothes and selecting them. The authors of [16] presented a system integrating Microsoft Kinect with a game engine, i.e., Unity. Differently than in the previous work, tracking data were used to animate a personalized 3D avatar representing the customer. The avatar is created in three stages: in the first stage, several photos of the customer (30/40) are exploited to generate a 3D model of the head; in the second stage the rest of the body is generated by fitting customer-provided measurements to an antropomorphic template; in the last stage, the head and body models are combined. The deformations of clothes, generated with Marvellous Designer, are simulated by using a Unity asset. More recently, the authors of [17] proposed a collaborative system that leverages a monocular RGB camera and the MediaPipe framework to track the movements of a potential customer. The term collaborative refers to the possibility for another user to support the customer during a shopping experience by means of a voice call. The system also features real-time cloth simulation using Unreal Engine and the uDraper plugin. The work confirmed the possibility to generate hyper-realistic simulations using the mentioned game engine and plugin. Like in other studies, the avatar is reconstructed by customizing a template model with MB-Lab[26].

To the best of the authors' knowledge, a single solution based on state-of-the-art techniques supporting all the functionalities required for the creation of a VFR experience mentioned in the above review is lacking. Hence, the present work tries to fill this gap by introducing a pipeline to develop VFRs in which a realistic representation of the customer body is generated by fitting a 3D avatar described using the SUPR parametric model to two input photos. The avatar is then integrated into a virtual experience created using Unreal Engine, which allows the customer to animate his or her avatar dressed with a chosen digital garment in real time by moving in front of a camera. Functionalities for trying on different garments and sizes are also provided.

PROPOSED PIPELINE

The overall pipeline is depicted in Figure 1. The steps for letting a customer try a digital garment on are

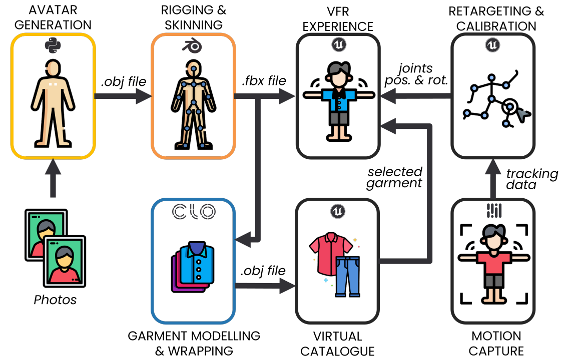


FIGURE 1: Proposed pipeline.

as follows: i) generation of the customer's avatar, ii) automatic rigging and skinning, iii) garment modeling and wrapping, iv) selection of the garment from the catalogue, v) starting of the experience in the VFR, vi) motion capture, and vi) retargeting of the animation data between different skeletons. More details on each step are provided in the following.

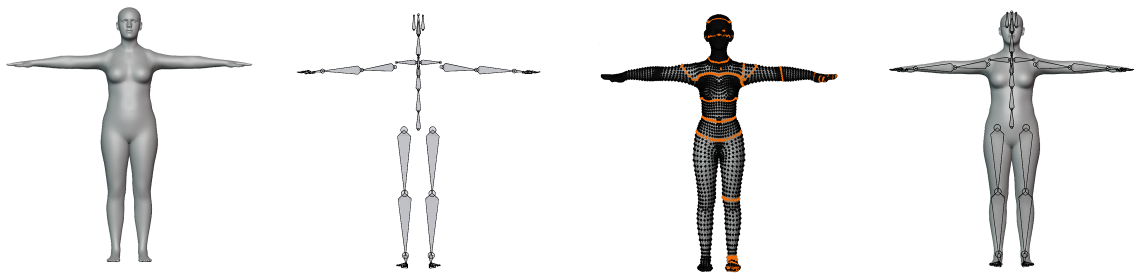
Avatar generation

The first step encompasses the creation of the customer's avatar. To this aim, the AI-based architecture proposed in [18] was extended to generate avatars described with the SUPR parametric model (more details on SUPR are available at https://supr.is.tue.mpg.de/). In particular, changes made were aimed to make the architecture support SUPR (as it was originally designed to operate with a previous version of the model) and to optimize some components, such as the Batch Normalization layer in the auto-encoder and the image segmentation module. Details are provided in a separate work [19]. A minimalist Graphics User Interface (GUI) was created to support the customer in the generation process. Through the interface, he or she can specify some basic parameters, i.e., gender, height, and weight and take two pictures, front and side that are provided as input to the generation algorithm. The algorithm returns an avatar described using the SUPR model in the *.obj* file format. To obtain the best results in terms of body similarity, the customer is requested to assume a T-pose and not be hardly dressed.

Rigging and skinning

Once the 3D model of the avatar has been generated, it needs to undergo rigging and skinning. Rigging aims to create a hierarchical structure of bones (referred to as a skeleton) that is embedded in the mesh to make it assume the requested poses. Afterwards, skinning is

[26]MB-Lab: https://mb-lab-community.github.io



(a) (b) (c) (d)

FIGURE 2: Rigging and skinning procedure: a) .obj file imported into Blender, b) template of the skeleton compliant with the SUPR definition [10], c) vertex groups of defining key segmented regions, and d) resulting avatar ready to be animated.

used to establish a binding between the mesh and the skeleton, by defining the degree of influence (namely the weight) that each bone exerts on the vertices of the mesh.

The above operations were automated by means of a Blender addon, named Rig-SUPR [20]. More specifically, the user is requested to import into Blender the file previously generated as .obj file (as shown in Figure 2a). To this aim, built-in functionalities of the software are leveraged. Then the Rig-SUPR addon inserts a new skeleton (within the 3D mesh of the avatar) by copying and pasting the template of a skeleton compliant with the SUPR definition [10] (that is depicted in Figure 2b). A methodology was developed to adapt the pre-computed skeleton to different avatar body shapes by identifying specific vertex groups, each defining key segmented regions (like arms and hips) on the mesh. Sample vertex groups are highlighted in Figure 2c. To identify the vertex groups, the methodology takes advantage of the SUPR model's consistency across meshes, ensuring identical vertex indices for each avatar. Once the vertex groups are established, their centroids are used to place and transform bones making them fit the target positions, thus completing the rigging process. Skinning is achieved by transferring the weights of bones' influence on the vertices from the template to the avatar. Again, the SUPR model's consistency is leveraged to identify bones, vertices, and corresponding weights to be transferred. The result of the rigging and skinning process is reported in Figure 2d.

The last step to make the generated avatar compliant with the SUPR model is the transferring of blendshapes. In the template provided with the SUPR model, a number of blendshapes are defined to control the general shape of the avatar (300 blendshapes), its facial expression (10 blendshapes) and the corrective poses (400 blendshapes) [10]. The devised addon automatically generates the blendshapes by transferring them from the SUPR template. These blendshapes are then used in the subsequent stages of the pipeline to animate the generated avatar.

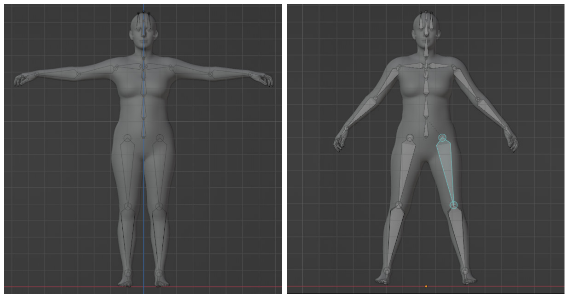
Rig-SUPR also changes the pose of the generated avatar, passing from the T-pose (Figure 3a) to the A-pose (Figure 3b). This operation is needed to optimize some of the next steps of the pipeline, i.e., the wrapping of the clothes and the initialization of the VFR experience (more details will be given in the following). The avatar in A-pose is exported as a *.fbx* file.

Although most of the operations referring to the reconstruction of the avatar and its use in the remaining steps of the pipeline are automated, it should be noted that some manual operations are still required, e.g., to import/export the file from Blender to Unreal. This aspect may impact the scalability of the devised solution. Developing end-to-end (fully automated) solutions may speed up the overall process but could also introduce constraints regarding flexibility.

Garment modeling and wrapping

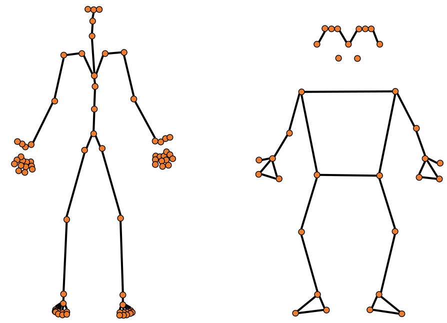
CLO3D was selected for creating 3D garment models due to its versatility in designing digital clothes, either through built-in modeling tools or by converting traditional sewing patterns into 3D geometries. Moreover, it allows the designer to import "ready-to-use" models from online repositories, such as Turbosquid[27], CG Wardrobe[28] and CGTrader[29]. CLO3D also includes

[27]Turbosquid: https://www.turbosquid.com/
[28]Wardrobe: https://cgwardrobe.com/
[29]CGTrader: https://www.cgtrader.com/



(a) (b)

FIGURE 3: Avatar based on SUPR a) as generated, in T-pose, and b) converted in A-pose by Rig-SUPR.



(a) (b)

FIGURE 4: Differences in terms of topology between the a) SUPR [10] and b) MediaPipe skeleton.

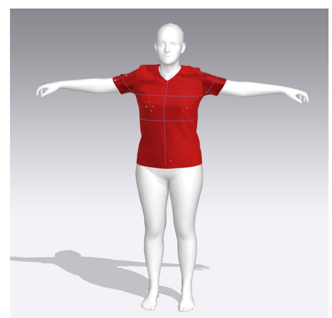


FIGURE 5: Artifacts generated around the shoulders during wrapping when the avatar is in T-pose.

functionalities that can be leveraged to easily generate different sizes of the same garment. In this work, three different sizes, i.e., small, medium, and large were created for each of the models used. For what it concerns fabric properties, it is possible to manually configure them, or leverage material libraries made available on platforms like FashionPrompts[30].

Finally, it is worth noticing that the functionalities of CLO3D and its compatibility with the proposed pipeline ensured seamless integration of personalized avatars in the design of the garment and its simulation. More specifically, to finalize a garment model and satisfy the requirements of the VFR application, the simulation of its wrapping on the avatar's shape is needed; in other words, it is necessary to compute the garment deformations according to the properties of the fabric and the customer's body. Although CLO3D includes a number of basic avatar templates that can be personalized with body measurements for this purpose, it has been chosen to leverage the avatar generated in the previous step of the pipeline, thus improving the realism of the VFR experience. The avatar is imported in A-pose, since it was observed that, with the T-pose, the cloth simulation could generate unnatural creases in the shoulder areas (Figure 5); moreover, the close position of the legs of the T-pose could produce artifacts in the simulation of clothes covering the lower part of the body.

Once all the above operations are completed, the garment model is exported in *.obj* format, with each size of the model stored as a different file. The files are collected into a virtual catalogue, i.e., a folder inside the Unreal Engine project that is leveraged by the customer to select the digital garment during the VFR experience.

Motion capture

As anticipated, the Google's MediaPipe was selected to track the customer's movements through a monocular RGB camera. In particular, the MediaPipe4U[31] plugin is used, since it offers a suite of libraries and tools for embedding MediaPipe's machine learning functionalities in Unreal Engine projects.

As discussed above, the skeleton of the avatar generated in the previous steps of the pipeline is compliant with the SUPR skeleton, which differs in terms of bones from the skeleton tracked by MediaPipe. Differences between the two skeletons are depicted in Figure 4.

For this reason, a mechanism is needed to remap the tracking data from the MediPipe to the SUPR skeleton. To this aim, the MediaPipe Remap Asset tool is leveraged. The remapping operation needs to be carried out only once, since the obtained configuration can be reused for all the avatars generated according to the described pipeline that are passed as input to Unreal Engine.

[30]FashionPrompts: https://www.fashionprompts.com

[31]MediaPipe4U: http://github.com/endink/Mediapipe-plugin

The MediaPipe4U plugin also offers functionalities that can be used to automatically optimize the pose of the avatar and correct the rotations of bones in case they are tracked inaccurately. These functionalities were not activated since they were found to be optimized only for the Unreal Engine standard avatar, yielding to artifacts with other avatars.

VFR experience

The rigged customer's avatar and the digital garments are imported into Unreal Engine and used in the VFR, where the GUI supports interaction with a virtual catalogue (Figure 6). Considering the prototypical nature of the solution proposed in this work, it was decided to include in the virtual catalogue only a limited number of garments, i.e., a top, a jacket, a T-shirt, a pair of pants, a dress, a hat, and a bag. Although new garments can be easily added to the VFR experience by importing the .obj files in the Unreal Engine project folder, it is also worth mentioning that a redesign of the GUI would be needed, as the current solution that presents all the available garments in the same window would be not scalable. For instance, garments could be grouped into categories and filters added to show only items reflecting desired characteristics.

To enable real-time cloth simulation, the uDraper plugin is utilized. During the simulation, collisions between the fabric and the avatar's mesh must be computed. To this aim, it is advisable to use a mesh with lower details to limit the number of calculations per frame and achieve real-time performance. Unreal Engine provides functionalities for automatically generating new meshes with different Levels Of Detail (LODs). For the purposes of the VFR simulation, starting from the imported avatar only one single additional LOD is created, which is used for handling collisions. In the VFR experience, only the original mesh is displayed (Figure 6a).

MediaPipe4U does not place any constraints on the camera to be used for video acquisition and this makes it a very flexible tool. However, it also entails the need to introduce a calibration phase, aimed at correcting inaccurate positions/orientations of bones (e.g., to avoid the avatar's chest to lean forward in an unexpected way) and determining the distance of the customer from the camera to set up depth information. The calibration takes place every time the camera is activated, and requests the customer to assume the A-pose for a few seconds (Figure 6b).

Once calibration is completed, the customer can start to move in front of the camera to animate the avatar (Figure 6c). The position and orientation of the

(a)

(b)

(c)

FIGURE 6: GUI of the VFR application when the customer is a) selecting a garment from the virtual catalogue, b) calibrating the pose, and c) animating the avatar through motion capture.

bones tracked with MediaPipe are also leveraged to activate the corrective blendshapes of the SUPR model. The logic that controls the activation of the blendshapes is embedded into an Unreal Engine script, which also updates the positions of some vertices in order to avoid unnatural deformations.

The uDraper plugin supports the simulations of multiple garments in the same session, hence the customer can build up his or her outfit by interacting multiple times with the virtual catalogue.

EXPERIMENTAL EVALUATION

A user study was carried out to compare a VFR experience generated through the proposed pipeline (later referred to as P) against representative alternatives. More specifically, the study compared P against two commercial tools, i.e., Wearfit and WANNA Wear.

Wearfit is an online platform that allows customers to provide a set of body measurements (i.e., height and weight for a quick configuration, or height, chest, waist, and hips for a more complex setup) in order to customize a non-animated mannequin on which clothes with different sizes and colors can then be displayed. The platform provides recommendations on the size to be chosen according to provided body measurements and includes the possibility to activate a visualization for checking size fitting. In the following, this solution will be referred to as S (for static mannequin).

WANNA Wear is a mobile app available for iOS devices, which leverages AR technology to superimpose virtual clothes on the customer's body framed through the device's camera. Although this app is quite popular and used by several brands, similarly to other AR solutions, it is characterized by a limited-quality cloth simulation resulting into rather stiff garments during animation. In the remaining, this solution will be referred to as AR.

The two alternatives were selected as they exhibit complementary characteristics, well representing the spectrum of possible VFR features. AR uses the real images of customers, whereas S relies on a static mannequin; S, in turn, is able to offer a higher-quality cloth simulation, but not the level of interactivity of AR. In P, these features are integrated in a single tool.

The goal of the experiment was to assess the ability of the considered alternatives to offer a VFR experience that is realistic enough in terms of avatar visualization and cloth simulation, help the customer choose the correct size of the selected cloth, increase satisfaction at using the technology for the given purpose, and raise confidence in the purchase of a garment tried virtually.

Metrics

To fulfill the above goals, subjective measurements were collected by asking the study participants to fill in a post-test questionnaire that investigated the following dimensions: usability [21], virtual embodiment [22], perceived functional value [23], perceived experimental value [23], adoption intention [24], purchase intention [25], and model accuracy [25], [26]. The metrics used to investigate these dimensions as well as the items included in the questionnaire were based on standard tools from the literature. Items were rated on a 1-to-5 Likert scale, from "strongly disagree" to "strongly agree".

Finally, the participants were asked to express their preference for the three VFR alternatives by ranking them in terms of enjoyment and fitting experience. The questionnaire is available for download at http://tinyurl.com/bdruwbct.

Hypotheses development

The considered metrics were linked to hypotheses with the final aim of evaluating the effectiveness of P compared to AR and S. More specifically, the following hypotheses were formulated:

- Hypothesis 1 (usability): Compared to AR, P does not suffer from potential tracking instability and occasional inaccuracies that arise when overlaying garments on real-time images. Moreover, P offers an interactive experience that allows users to control the movements of their personalized avatar, in contrast with S where a static mannequin is used. Therefore, it was expected that "*P can achieve the best results in terms of usability SUS scores among the three alternatives (H1)"*.
- Hypothesis 2 (virtual embodiment): The personalized 3D avatar generation in P, leveraging the SUPR parametric model, should provide a stronger sense of ownership than the static mannequin used in S. Moreover, the possibility to present real images with AR should reduce the gap with P, which is able to animate the avatar using motion capture. Therefore, it was expected that "*P can outperform S in both ownership and agency and achieve comparable agency scores to AR (H2)"*.
- Hypothesis 3 (perceived functional value and functional experimental value): The combination of high-fidelity avatars, interactive motion capture, and realistic garment simulation proposed in P was meant to enhance both the functional and experiential aspects of the VFR experience. Therefore, it was expected that "*P can provide the highest perceived functional value (usefulness) and experimental value (enjoyment and curiosity) (H3)"*.
- Hypothesis 4 (adoption intention, purchase intention, and model accuracy): The use of Unreal Engine and the uDraper plugin should enable detailed cloth physics and realistic graphics simulation, making P more engaging and likely to drive adoption compared to AR and S. Moreover, the static visualization and the limited quality of the AR overlays should limit the satisfaction of the participants when using S and AR. Therefore, it was expected that *"P can lead to the highest adoption and purchase intention, obtaining superior scores in model accuracy metrics, including graphic vividness and 3D authenticity, compared to AR and S (H4)"*.

Participants

Overall, 25 participants (18 male and seven female) were involved in the study. Participants were aged between 21 and 64 (*M* = 30.20, *SD* = 11.13). According to data collected through a demographics questionnaire administered before starting the experiment, the sample was quite heterogeneous regarding willingness to go shopping, since only 52% of them showed high levels of interest in activities related to shopping and appreciation in doing such activities. Most of the participants agreed on the fact that what they purchase represents their personality (96%) and they would feel angry if shopping turned out to be a bad use of their time (80%). These data indicated their possible interest in solutions capable of improving the shopping experience.

Procedure

The experiment followed a within-subjects design. More specifically, after having completed the demographic questionnaire and received general instructions on the experiment, all the participants were invited to familiarize with the three alternatives. When they said to feel confident in using all the alternatives, they were requested to use each of them to virtually try on a number of predefined clothes. After the experience, they were requested to fill in the post-test questionnaire. The order for using each alternative was randomly assigned to limit bias.

RESULTS

Before analyzing the statistical significance of the observed results, the Cronbach's α was used to asses the reliability of the study. Previous studies, such as [8], recommended a Cronbach's α value greater than 0.7 to consider reliability as acceptable. As it can be observed in Table 1, all the explored dimensions show Cronbach's α values greater than 0.7, suggesting that results could be regarded as reliable.

The statistical analysis was performed by using the Friedman Test, whereas for pairwise comparisons the Wilcoxon Signed-Rank Test for paired samples was used.

The first section of the questionnaire investigated usability using the System Usability Scale (SUS) [21]. The participants expressed a high appreciation for all the alternatives, as the overall scores were higher than 80.3 (corresponding to "Excellent" in the Adjective rating scale). However, statistically significant differences were observed among the three alternatives ($p < .001$). More specifically, the participants rated P and AR as more usable than S (P: 91.80 vs S: 86.20, p = .003; AR: 89.40 vs S: 86.20, $p < .001$). Although no statistically significant differences were observed between P and AR, it is possible to conclude that P and AR provide the most usable solution, thus confirming H1.

TABLE 1: Cronbach's α values for the considered dimensions.

Dimension	AR	P	S
Usability	0.747	0.760	0.737
Ownership	0.713	0.845	0.823
Agency	0.701	0.792	0.714
Usefulness	0.834	0.702	0.911
Enjoyment	0.963	0.948	0.937
Curiosity	0.927	0.796	0.917
Adoption Intention	0.896	0.840	0.830
Graphic Vividness	0.843	0.780	0.747
3D Authenticity	0.802	0.718	0.851
Purchase Intention	0.770	0.752	0.701

Regarding the other dimensions, evaluated through the remaining sections of the questionnaire, Table 2 reports the average scores for individual statements, whereas Figure 7 summarizes the results by averaging the statements in each dimension (after having converted all the scores into a worst-to-better scale).

Virtual embodiment, addressed in the second section, was studied by evaluating ownership (Figure 7a) and agency (Figure 7b). Ownership refers to the sense of similarity between the avatar and the real body of the participants. Agency focuses on aspects regarding the control that participants had over the movements of their avatars. Starting from ownership, it was noticed that AR outperformed the other two alternatives ($p < .001$). In particular, AR (4.81) was judged to be better than P (4.37, p = .002) and S (2.60, $p < .001$) at conveying the sense of body ownership. This result can be explained by the fact that the AR alternative uses the real images of the participant to superimpose garments rather than relying on a reconstructed or poorly personalized avatar. Statistically significant differences were also observed between P and S, in favor of the former ($p < .001$). This means that the reconstructed participant's body was judged to be more similar to the one that could be configured in S, thus confirming the effectiveness of the approach used in this work for the automatic avatar generation. Similar results were also observed for agency. In fact, statistically significant differences were observed among the three solutions ($p < .001$). Specifically, with AR (4.82) the participants reported an improved sense of agency with respect to both P (4.62, p = .009) and S (1.15, $p < .001$). Similarly to what was observed for ownership, P was

TABLE 2: Subjective results: average scores for individual statements with the three alternatives.

	AR	P	S	p-value
Ownership				
OS1. It felt like the virtual body was my body.	4.84	4.00	2.24	<.001
OS2. It felt like the virtual body parts were my body parts.	4.76	4.44	2.40	<.001
OS3. The virtual body felt like a human body.	4.96	4.92	3.68	<.001
OS4. I felt like the virtual body belonged to someone else.	1.44	1.60	3.48	<.001
OS5. It felt like the virtual body belonged to me.	1.44	1.60	3.48	<.001
Agency				
AG1. The movements of the virtual body felt like they were my movements.	4.96	4.68	1.00	<.001
AG2. I enjoyed controlling the virtual body.	4.60	4.80	1.52	<.001
AG3. I felt like I was controlling the movements of the virtual body.	4.96	4.64	1.12	<.001
AG4. I felt like I was causing the movements of the virtual body.	4.80	4.68	1.12	<.001
AG5. The movements of the virtual body were in sync with my own movements.	4.80	4.28	1.00	<.001
Usefulness				
PU1. VFRs can aid me in evaluating garment fit for online apparel shopping.	2.76	4.40	3.20	<.001
PU2. Using VFRs will enhance my shopping effectiveness by reducing fit problems.	2.68	3.80	2.64	<.001
PU3. Using VFRs will increase my shopping productivity through aiding me in evaluating garment fit.	2.80	4.04	2.96	<.001
Enjoyment				
PE1. Using VFRs for online apparel shopping will be enjoyable.	3.84	4.52	2.72	<.001
PE2. It will be a pleasant experience to use VFRs for online apparel shopping.	3.80	4.40	2.68	<.001
PE3. I would have fun using VFRs.	4.16	4.60	2.56	<.001
Curiosity				
PCR1. Using VFRs will stimulate my interests.	3.40	4.00	2.76	<.001
PCR2. Using VFRs will satisfy my curiosity.	3.60	4.44	2.92	<.001
PCR3. Using VFRs will arouse my imagination.	3.60	4.08	3.00	<.001
Adoption Intention				
AD1. I intend to use VFRs in the future for my apparel shopping.	3.12	3.76	2.40	<.001
AD2. It is very likely that I would use VFRs in the future.	2.76	3.44	2.24	<.001
AD3. I expect that I will use VFRs in the next time I shop.	2.28	2.84	1.88	<.001
Purchase Intention				
PI1. After playing the experience with the garment model, how likely is it that you would consider to go test the real garment model?	4.72	3.44	3.96	<.001
PI2. The fitting experience would be helpful in aiding me to make a purchase decision if I am considering buying a garment.	2.60	3.96	2.84	<.001
PI3. The fitting experience would increase my intention to buy the garment model I try.	2.36	3.60	3.00	<.001
PI4. I would be willing to recommend to my friends to use the fitting experience as a decision aid when considering what garment to test buy.	3.28	4.12	2.64	<.001
Graphic Vividness				
GRA1. There are lots of graphics in the game.	2.72	4.76	1.64	<.001
GRA2. Graphics of the garment, and the outside environment, let me visualize what the real garment might look.	2.48	4.64	2.12	<.001
GRA3. The garment and the outside environment illustrated by 3D graphics was very real.	2.24	4.40	2.68	<.001
3D Authenticity				
3DA1. 3D creates an experience similar to the one I would have when wearing in a real fitting room.	2.92	4.32	2.72	<.001
3DA2. 3D lets me feel like as if I am wearing a real garment.	3.00	4.36	2.44	<.001
3DA3. 3D lets me feel like as if I am really test how a garment fit to me.	2.52	4.12	2.76	<.001
3DA4. 3D lets me see the garment as if it was a real one.	2.20	4.20	2.92	<.001

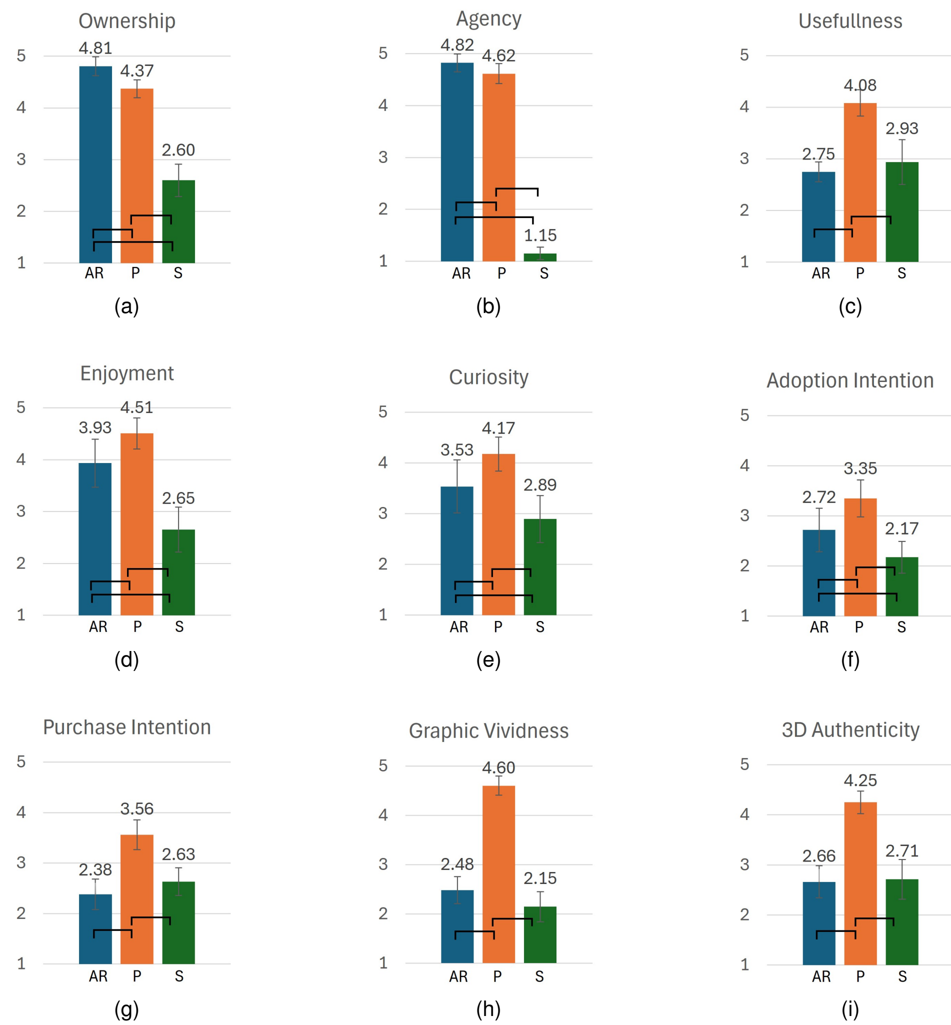


FIGURE 7: Subjective results in terms of a) ownership, b) agency, c) usefulness, d) enjoyment, e) curiosity, f) adoption intention, g) purchase intention, h) graphic vividness, and i) 3D authenticity.

preferred to S ($p < .001$). The P alternative was probably less appreciated than the AR one, since the latency introduced by the use of MediaPipe negatively affected the experience. The poorer results achieved by S are mainly related to the fact that the participants are not allowed to control the movements of the avatar. These results partially support H2, as scores assigned by the participants for ownership and agency indicate that AR was preferred to P for both the dimensions.

The third section was aimed at evaluating the perceived functional value of the three alternatives. This dimension was studied by asking the participants to rate the usefulness (Figure 7c), i.e., the capacity of the alternative to make them evaluate the suitability of the garment during a shopping experience. Significant differences were observed among the three groups ($p < .001$). In particular, P (4.08) was considered better than AR (2.75, $p < .001$) and S (2.93, $p < .001$) to support fitting. On the one hand, these results confirmed that, although AR lets the participants visualize their real bodies, superimposing the synthetic cloth on them was not the best solution. In fact, tracking errors and the lack of accurate physics simulation made the participants be poorly confident of the size fitting, thus considering this alternative not useful for this aim. On the other hand, although S supports different sizes and provides recommendations on the best fit, the participants found it difficult to evaluate the actual fit since the avatar is static; therefore, they could not see their movements transferred onto the avatar while trying the cloth on.

The perceived experimental value tackled by the fourth section was studied by asking the participants to rate the extent to which they enjoyed using the specific alternative (Figure 7d) and the level of curiosity (Figure 7e), i.e., its capacity to stimulate interest and imagination. Concerning enjoyment, significant differences ($p < .001$) were observed among the three alternatives. P (4.51) was found to be able to let the participants have more fun than both AR (3.93, $p = .001$) and S (2.65, $p < .001$). Moreover, AR was judged as superior to S ($p < .001$). The same ranking is also observed for curiosity, where P surpassed both the other alternatives ($p < .001$). More specifically, P (4.17) was judged to better stimulate curiosity than both AR (3.53, $p = .001$) and S (2.89, $p < .001$). Differences between AR and S were also significant ($p = .002$). The results regarding perceived experimental value are aligned with those observed in the previous section. In fact, the ability to make the participants perceive an improved sense of usefulness also makes the overall experience more enjoyable and stimulating. The low interactivity (i.e., limited control over the avatar) provided by S is reflected in a lower appreciation of this alternative.

The above results strongly demonstrate H3, as P was rated as the best alternative with respect to both S and AR for all the considered metrics.

The greater appreciation for P with respect to AR and S is also confirmed by the analysis of the intention to adopt such kind of technology in the future ($p < .001$) and the intention to actually purchase a garment after having used it ($p < .001$), investigated in the fifth and sixth sections. More specifically, analyzing the adoption intention, the participants reported a greater interest in using P (3.35) than both AR (2.72, .002) and S (2.17, $p < .001$). The results also showed that S was outperformed by AR ($p = .003$).

Considering the purchase intention, again P (3.56) was judged to better support the participants in the actual purchase of the tried clothes with respect to both AR (2.38, $p < .001$) and S (2.63, $p < .001$). It is worth observing that, although P outperformed the three alternatives, the scores assigned by the participants to these dimensions are generally low or under the medium scale value. This result suggests that further improvements are needed to enhance the experience with these tools, increasing the customers' intention to use and purchase the garments they tried on.

Concerning the model accuracy dimension tackled in the seventh section, it was chosen to evaluate it in terms of both graphic vividness, i.e., the quality of the graphics and physics simulation displayed to the customer, as well as 3D authenticity (Figure 7i), i.e., the ability of the displayed graphics contents to make the customer perceive the VFR experience as real. Significant differences were observed among the three interfaces for what it concerns both graphic vividness ($p < .001$) and 3D authenticity ($p < .001$). Starting from graphic vividness, the results confirmed the superiority of P (4.6) with respect to both AR (2.48, $p <$ .001) and S (2.15, $p < .001$). No significant differences were observed between AR and S. Similarly, P (4.25) outperformed both AR (2.66, $p < .001$) and S (2.71, $p < .001$) in terms of 3D authenticity. In the case of AR, these results can be explained by the fact that only a portion of the visualized image, namely the participant's body, is perceived as realistic; the limited cloth simulation and the issues with clothes that were not properly superimposed on the participants' body had a strong impact on the evaluation. For what it concerns S, the impossibility to control the avatar and the lack of a real-time cloth simulation made the participants perceive the experience with this alternative as less realistic (more synthetic/digital) than with P.

Although some areas for improvement were noted, P outperformed the two alternatives in terms of adoption intention, purchase intention, and model accuracy. This finding strongly supports H4.

Finally, the participants were requested to rank the three solutions in terms of overall enjoyment and VFR experience. The expressed rankings were aligned with the results discussed above. More specifically, P was the most appreciated alternative, obtaining in both the rankings the largest number of preferences. AR was judged as the second alternative for what it concerns enjoyment. However, limitations related to tracking accuracy and cloth simulation experienced with it made the participants rank it third for what it concerns the VFR experience.

CONCLUSION AND FUTURE WORKS

This paper presents a unified pipeline supporting the creation of VFR experiences based on state-of-the-art techniques. In particular, the proposed pipeline includes the generation of a high-fidelity representation of the customers' body based on the SUPR parametric model. Motion capture based on a monocular RGB camera is enabled using MediaPipe, thus letting customers transfer body movements on their avatars. Besides motion capture, the VFR experience supports real-time simulation and visualization of cloth deformations through an interactive Unreal Engine application and the uDraper plugin. Finally, the pipeline integrates CLO3D for garment design and wrapping.

It is worth noting that the implementation of the pipeline reported in the present paper relies on specific tools and libraries (e.g., SUPR, Blender, Unreal Engine, and uDraper). This aspect could appear to limit the ability of the proposed solution to generalize. However, the modularity of the pipeline makes it possible to replace individual components with minimal impact on the overall workflow. For instance, the first part of the pipeline, which focuses on reconstructing a fully 3D avatar ready to be animated, has already been tested with another game engine (i.e., Unity 3D) in [20]; in the present work, Unreal Engine was chosen to enhance the visual quality of the VFR experience. Moreover, it would also be feasible to replace the generative component of the SUPR avatar with commercial tools, such as MetaHuman Creator[32]. In such cases, only minor adjustments would be required in the Unreal Engine application to accommodate the different skeleton topology.

A user study aimed at comparing the VFR experience that could be created with the pipeline presented in this paper against those obtained using two commercial tools was carried out by involving 25 participants. Subjective measurements collected during the experiments showed the advantages offered by the VFR created with the proposed pipeline in terms of usability, virtual embodiment, perceived functional value, perceived experimental value, adoption intention, purchase intention, and model accuracy. These results were also confirmed by analyzing the rankings regarding enjoyment and fitting experience. Despite the promising results, it is worth noting that a potential bias could arise due to the limited sample size (25 participants) and a non-uniform distribution between male and female participants. Further experiments are needed to address the above limitation and verify whether the results can be replicated with a larger sample size and a different participants distribution. Moreover, in general, scores assigned to the intention to use and purchase were not so high; hence, new functionalities aimed at improving the customer experience could be introduced and validated through a new experiment. Besides limitations regarding the experiments, possible weaknesses in using the devised solution should be highlighted. In particular, in the VFR experience created with the proposed pipeline, the customer is required to assume a specific pose and not to be hardly dressed when capturing the photos used to generate the avatar. Future works will be devoted to coping with issues like this one, e.g., introducing novel techniques for the generation of avatars that are less influenced by the pose and dress of the customer. For instance, so far the pipeline is able to reconstruct only the customer's body, without considering the face, hair, skin, etc. In the future, methodologies able to transfer in the generated avatar other characteristics of the customer will be investigated. Finally, another limitation of the current implementation regards the use of MediaPipe that, in some cases, is characterized by a high latency and inaccurate poses. Further efforts will be devoted to improve this component by considering alternative technologies.

[32]MetaHuman Creator: https://www.unrealengine.com/en-US/metahuman

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