A3Cplus - Efficient Anatomically Accurate Avatar Creation

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ABSTRACT

Virtual reality applications are witnessing increased adoption in mental and physical health fields, from rehabilitation therapies to psychological studies. The more advanced the application, the greater the demand to incorporate realistic, custom avatars based on the participant's physical characteristics to enhance embodiment. Current solutions focus on creating such avatars by using expensive camera arrays to capture a 3D representation, which requires technical skills and actively involves the participant in the process. However, equipment and space requirements, setup complexity for non-technical operators, and physical challenges for participants often lead to difficulties and high costs for consistent adherence. This paper presents A3Cplus, a tool to efficiently generate anatomically accurate avatars based solely on a small amount of participant phenotypic data. An optimized processing pipeline uses this data to manipulate specialized blend shapes automatically and mold a generic model into the correct dimensions. We provide illustrative examples of using our tool and discuss its general applicability to immersive avatar-based virtual environments that require a high degree of accuracy and embodiment.

CCS CONCEPTS

• **Computing methodologies** → **Shape modeling**; **Virtual reality**; • **Human-centered computing** → *Accessibility systems and tools*; • **Applied computing** → *Psychology*.

KEYWORDS

Avatar Creation, Blend Shapes, Clinical and Therapeutic Applications, Virtual Reality, Immersion

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1 INTRODUCTION

With the increasing availability and capabilities of Virtual Reality (VR) technologies, their significance has surged, ushering in new possibilities for immersive experiences and research. The unique properties of VR systems that enhance these experiences are best showcased when we can control the entire environment and provide a full-body immersion that engages the participant's body within a virtual environment. We are able to view objects and environments from multiple perspectives, observe changes in real time, and visualize how they would appear with alterations. The capability enables us to gain insights into aspects that are typically challenging to perceive directly. More formally, a full-body immersion within a virtual environment allows the user to experience a sense of embodiment [5], which combines the feelings of being present, owning their physical form, and exerting agency control over it. By optimizing these three elements, more convincing body illusions that enhance exploration and interaction with the virtual world as if one is truly present can be established.

These illusions are particularly useful when considering research combining VR and clinical psychological and physical treatments. VR has already been successfully applied across a wide range of issues, including pain management [9], anxiety [8] rehabilitation of gait [2], and even learning to use new tools like wheelchairs [11]. While these studies have provided valuable insights into the effectiveness of these novel treatments, they are almost exclusively conducted in isolation from a technical front, making it challenging to compare results across various studies.

According to a meta-analysis published in 2018 [3], several obstacles remain in VR applications for clinical settings and psychological experiments. These challenges include limited trials in non-lab settings, the technical expertise required, lack of standardization across studies, and overall costs. As these applications of VR are still in their infancy, it is not difficult to see that there are no trivial problems to solve. In fact, a further analysis from 2022 [4] confirms that many of the same challenges continue to persist in this field.

A major aspect that poses a significant barrier to entry for an effective full-body illusion, is the requirement for a realistic 3D avatar. Studies have demonstrated that realistic avatars can improve the sense of body ownership [12] and enhance the subjective experience for the participant [6]. For an effective experience, customizing the avatar to align with body shape, dimensions, and other phenotypic properties is crucial for achieving a high-quality embodiment. Unfortunately, the most commonly used solution is high-quality scanner-like systems, which introduce a substantial ongoing cost for the end user. These costs are associated with obtaining and maintaining the scanning equipment, in addition to the ongoing learning process. Furthermore, unique challenges also present themselves due to the highly sensitive nature of the data in a clinical or psychological application. These contexts demand strict adherence to privacy and data protection regulations to protect patient information. Another challenge is that not all users may have the ability to enter the machine to get an optimal scan, limiting their ability to receive treatment. Looking beyond stationary care, chronic therapies also pose a challenge when the health of the

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body recovers (or worsens) at a faster rate, requiring more frequent rescan sessions to keep up with the progress.

These problems can be summarized by three requirements for this problem space. The first factor is the need for a *dynamic and consistent* system that can adapt to changes in the user's appearance over time. This includes the ability to accommodate alterations such as aging, body fitness or new features such as scars or a tan. These changes should also be reversible and applicable live within the VR application, enabling spontaneous, on-the-spot adjustments to maximize embodiment in as many situations as possible.

Secondly, we need to focus on *inclusive* solutions that cater to all participants involved in the process. This includes designing user-friendly systems for operators, requiring minimal cost, space, setup, maintenance, and reusability. Additionally, it should be optimized for accessibility for the users, accommodating individuals with physical impairments or forms of anxiety such as claustrophobia. Furthermore, it should be inclusive to developers of VR applications, allowing them to easily integrate it into their own projects, ensuring interoperability, compatibility, and consistency across different therapies and experiments.

Lastly, we need to focus on user *privacy* by minimizing the use of sensitive data for avatar creation. While creating the most accurate 3D representations is ideal, this usually requires using highly sensitive personal information, such as body scans or images. Doing so adds an extreme burden on operators to enact additional data management, security, and dealings with liability and potentially online 3rd parties. Scanning processes also affect participants by requiring them to wear specialized slim-fit clothes, which can be embarrassing and uncomfortable in front of others. It is crucial for users to have access to realistic avatars without sacrificing their privacy. Otherwise, it may deter and prevent them from receiving the treatments they need.

This paper presents A3Cplus, aimed at creating a dynamic, inclusive, and privacy-preserving avatar creation process. In Section 2, we provide an overview of existing tools used to create humanoid models, including commercial options and an in-depth analysis of two representative academic papers on their strengths and weaknesses. Throughout Section 3, we discuss in more detail the A3Cplus software, key features, and rationales that inspired its creation. Additionally, we introduce the process workflow, demonstrating how each feature contributes to simplifying its usage for the operator. We conclude the paper by discussing the broader implications of our tool along with areas for improvement, emphasizing the significance of general accessibility and applicability to immersive avatar-based virtual environments.

2 3D CHARACTER CREATION

This section examines various commercial and open-source tools on the market, and academic research conducted concerning 3D character creation, discussing their features to provide the relevant background behind the development of A3Cplus.

2.1 Commercial and Open-Source Software

Character creation tools are not limited to realistic avatars designed specifically for VR applications. Many established software packages offer robust solutions for character design in various contexts, including video games as prominent examples. Avatar-based video game genres, such as role-playing games, provide a vast array of character creation options for users to customize their characters. However, if these models are not limited to a single game, they can only be used in a narrow ecosystem of other games. Therefore, we limit the scope of software to those capable of integrating with any application by, e.g., exporting to 3D file formats. Overall, the software availability can be differentiated between *manual* and *automatic* creators.

A manual avatar creator is a software package focused on enhancing the experience for designers to configure different options to do with avatar creation manually. Examples of such applications include *Reallusion Character Creator* [1], *DAZ3D* [2] and *MakeHuman* [3]. All are intended to be used throughout the application development cycle before the application is shipped to the customer. This is because the tools have a high learning curve and have features to automatically import them into various game engine editors or export them to various 3D model data types.

While creating realistic, fully rigged, clothed, and textured avatars using these tools is simple, it is challenging to customize them based on accurate phenotypic measurements. However, this is not the goal of most of these tools, which were created for designers to make good-looking assets that fit into the specific design language of their applications.

The largest benefit to using manual avatar creators is that they operate offline and do not require any sensitive data to function, which helps maintain the user's privacy. As anatomical data cannot be incorporated due to missing measures, designers must rely on their artistic skills and knowledge of human anatomy to create a realistic avatar. This shows that while they are very inclusive to users, application developers, and operators who must prepare everything in advance, they do not provide a consistent and easy-to-use system. Looking at the output's dynamics, each application can export a functional humanoid rig. However, they each have their differences in the types of blend shapes that are available to export. DAZ3D stands out as the most dynamic manual creator as it enables the operator to export any available blend shape, with the added benefit of adding the body blend shape to attached clothes. Reallusion also allows for the export of blend shapes, but only when they pertain to facial expressions or are custom-made. However, the custom blend shapes only work correctly within the Reallusion editor itself, limiting their purpose outside the program. MakeHuman does not export any blend shapes at all, providing the least dynamic avatar export.

Automatic creators, on the other hand, rely on input images and apply algorithms to generate an avatar that can be used similarly to the manually generated avatar. Examples of such applications include *Meshcapade Me* [4] and *RealityScan* [5]. Both tools can produce lifelike representations of a human subject given a series of input images. Meshcapade Me is based on the skinned multi-person linear model (SMPL) [7], which operates via adjusting pose blend

[1] https://www.reallusion.com/character-creator/
[2] https://www.daz3d.com/
[3] http://www.makehumancommunity.org/
[4] https://www.meshcapade.com/
[5] https://www.unrealengine.com/en-US/realityscan/

shapes learned from thousands of 3D body scans. The user interface guides the operator through the process, allowing additional manual adjustments via sliders altering different phenotypic body measurements. RealityScan, like many other applications, applies photogrammetry techniques to images captured on a mobile phone to generate an output mesh automatically. This output mesh can then be used with services such as Mixamo [6] to automatically generate a rig for the human mesh. Meshcapade Me's avatars offer the greatest flexibility among the commercial alternatives due to using blend shapes as their building block. These shapes can be utilized throughout the model, providing dynamic animations inside the VR application. Note that these blend shapes may not have a clear definition from a human perspective as they were trained on data rather than being created by artists. On the other hand, applications such as RealityScan offer simpler functionality by providing an exact mesh that can be rigged for animation. They cannot dynamically alter body shapes without requiring manual creation using separate tools for each participant.

When looking at inclusivity from an operator's perspective, these tools provide a process of skipping the designing stage and going straight for reality. Still, the process on either application introduces opportunities for human error and requirements to rescan if something goes wrong. In addition, since there is no straightforward method for importing the generated models directly into VR applications, they must either be manually imported into an editor or imported fully at runtime. In terms of privacy, both programs require users to sign up for accounts and upload their input images for the service's hardware to apply the relevant algorithms to generate an output mesh. This process may raise concerns about data security and potential misuse of sensitive information. This feature alone makes it problematic or even impossible to include these options in clinical applications.

Overall, commercial applications create realistic-looking avatars and offer various customization options to adapt the avatar to the user. They typically export their models to common formats such as FBX, glTF, or obj, necessitating careful data management by the user and requiring developers to implement this functionality in their programs. However, these tools' significant limitations are either the absence of exact body dimension measurements or reliance on third-party platforms for generating anatomically accurate avatars.

2.2 Scientific Projects

3D character modeling encompasses a wide range of disciplines and technologies to achieve high-quality results.

One of the projects best resembling the goals of our study aims at creating a "Virtual Caliper" [10] for measuring the correct body dimensions using an HTC Vive headset and two SteamVR Lighthouse base stations. The authors present an application that allows for the creation of metrically accurate body shapes by utilizing the VR controllers as measuring points rather than relying on physically based methods. They employed user studies to identify the most effective measurement points for accurately capturing body dimensions in VR environments. By reducing the number of optimal measurements, they further refined the results by optimizing SMPL-based regressors based on these measures, ultimately landing on a few that became their user input in their process.

The result entails a process engaging the participant in following a guided walkthrough in VR. It is important to note that the tasks are entirely delegated to the participant rather than the experimenter. The measurements gathered from the six placements, as well as weight, are fed into custom SMPL linear regressors using least-squared computation to produce an avatar.

The study presents a model generation process that offers fast, guided, accurate, and privacy-aware body dimension measurement within VR environments. Although the resulting anatomy appears visually plausible based on input measurements, it lacks methods for adding textures such as skin color, clothing, or facial features. The application's reliance on the HTC Vive system limits its compatibility with other controllers and necessitates porting to different systems. Additionally, the user-guided process only applies to users who can stand up and go through the process, which may not be feasible for all individuals. The study showcases a desktop tool that allows for adjusting and exporting the model into FBX format, circumventing the virtual caliper process. Given that their results show subpar performance with real-life measurements and require post-processing adjustments to make the model more plausible, it indicates that it may not be well-suited for this specific task.

Another related study [1] focuses primarily on advancements in reconstructing human meshes out of a generic base model. To customize the base avatar model, the user must go through two separate 3D scanning steps. The first step consists of 40 DSLR cameras which capture the full body from a standing A-Position. In the second phase, a setup of 8 DSLR cameras captures the user from a sitting position, resulting in consistent facial scan information. For each scan, a point cloud is generated, where the goal is to align the base model with the new point set. After manually selecting nine landmarks on both the scan and the base model to wrap it around the point cloud.

The objective is to position the base model within the generated point cloud by automatically aligning nine key points from the base model to the scan. This is completed via a pose-optimizing pipeline, refining closest point correspondences and performing a fine-scale deformation to the initial point set. Textures are then computed based on camera images and refined or adjusted according to the presence of artifacts and the effectiveness of capturing details in unseen regions like under the arms. The facial reconstruction pipeline is similar. However, more features are transferred from the base model, such as its facial blend shapes. In addition, specific facial details such as teeth and eyes are retained from the original textures.

The finished product consists of the base mesh fitted and optimized to the structure given in the scan's point cloud. The authors showcase the flexibility of their approach by demonstrating how the textures of the newly created avatar can be effortlessly swapped between different scans having undergone the same treatment. This allows visual modifications to be even faster if only the texture needs to be altered. Since the procedure involved minimal manual intervention, consisting of selecting reference points and transferring images, the authors assert that it can be completed rapidly within 10 minutes.

[6] https://www.mixamo.com/

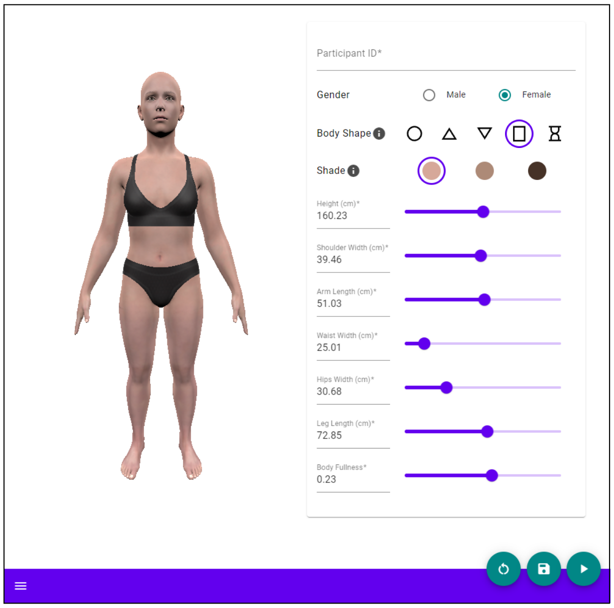

Figure 1: A3Cplus user interface.

Overall, both papers present distinct methods for generating realistic-looking avatars using unique and specialized techniques. Since both rely on base avatar models as their foundation, they are both very dynamic for use in VR applications. Despite this, they share limitations that may affect their inclusivity, such as reliance on specific hardware, substantial space requirements, and an assumption of a fully capable user to participate in the avatar creation process.

3 THE A3CPLUS AVATAR CREATOR

A3Cplus is a tool for efficiently creating anatomically accurate avatars designed to mitigate the limitations of existing solutions, as discussed in Section 2. We placed particular emphasis on simplifying the process and making it as non-technical as possible.

3.1 Tool Architecture

To achieve our goal of facilitating the avatar creation process, we opted for the *Keep it simple, Stupid!* (KISS) and *What you see is what you get* (WYSIWYG) philosophies. The KISS principle promotes developing simple systems as they work best in contrast to more complex systems. In the context of our tool, this means keeping the number of variables low, letting the operator see the entire program in one window without any drop-down menus or hidden options. On the other hand, WYSIWYG techniques center on allowing the resulting output to be seen directly within the editing window. Within our tool, this provides a sanity check for operators and a guarantee that the output model resembles the participant. Combining both, we can ensure a straightforward and intuitive user experience in our user interface, as shown in Figure 1.

The user interface is organized between two sections, featuring a spacious and bifurcated layout consisting of an output view and a controller view.

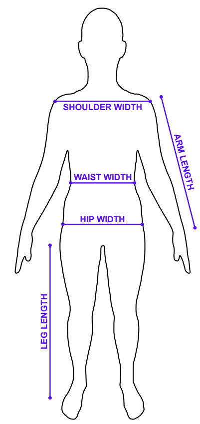

Figure 2: Main body measurements.

On the left side, the output view displays a live 3D-rendered scene with a uniformly lit humanoid model we use to project our measurements onto. The operator is free to adjust the position and rotation of the camera view to inspect the model from all perspectives to ensure it is correct. While the operator may interact and change the view on the model, they cannot alter any settings to do with changing the model directly.

The right side provides the operator an interactive space to seamlessly manipulate parameters that affect the model in real time on the output view. Here, the individual measurements can be applied, and non-visual metadata, such as participant ID, can be altered.

Combining both sides, the operator is guided linearly from the top to the bottom of the interface, ensuring a chronological and straightforward interaction from input to output.

3.2 Base Avatar

Due to the many advantages of the model outlined in Section 2, we chose to utilize DAZ3D's Genesis 9 model as a starting point for avatar creation. Compared to other options, by allowing full blend shape export and automatic generation of blend shapes for clothes, the avatars allow for simply and accurately incorporating extra features. While we utilized the available model for our initial implementation, our tool can be easily adapted to work with other base models. Utilizing a custom avatar could yield even more benefits and tailored results.

3.3 Blend Shapes and Optimization

Rather than wrapping the base model around a scan or basing the output on generalized blend shapes, we focus on modifying pre-designed, highly specialized blend shapes that carry human meaning, such as "Hip Size" or "Leg Length". This approach offers two advantages. First, by constraining changes to shapes that are plausible as human bodies, we ensure that our models remain realistic and grounded in human anatomy. Second, this enables developers to easily incorporate these shapes into their applications, allowing for live experiences where body shape can change dynamically.

To measure and adjust blend shape values based on phenotypic values, we first established methods of measuring the points of interest using our base model. Our aim was to create intuitive, systematic measurement processes that are easy for operators to understand, apply to a user, and implement into their procedures. We accomplished this by using the height and identifying key points of interest on the base mesh, labeled as indicated in Figure 2. These measurements represent specific aspects of human anatomy and could be easily measured by operators and generalized into combinations of blend shapes to represent an accurate body shape. The simplicity of the measurement process enables accessibility options as an avatar can be created while users are lying down, providing avatar options that include users with physical limitations.

With the measurements established and obtained, they are transferred to the base model. Some measurements, such as shoulder, leg, and arm length, are relatively simple to adjust since they operate independently of other measurements and can be achieved by utilizing blend shapes that proportionally adjust the relevant body parts. By making minute adjustments to these blend shapes, we can ensure that the measurements between the key points reflect the desired proportions.

The remaining measurements are more complex, as they involve working with multiple blend shapes simultaneously. As leg length is directly related to the height of the avatar, adjusting the height parameter only affects the upper body by stretching it until the height is reached, ensuring that each constraint is met. If both height and leg length are not set correctly, this can result in an unnatural body structure. On the other hand, when given valid values (where height is at least greater than leg length), the tool produces accurate and visually appealing height proportions.

The challenge becomes more complex when dealing with the body core. Humans come in various shapes and sizes, making it challenging to create a single set of blend shapes that accurately represents all bodies. To address this issue, we leverage the principles of *body shapes*, which are well-established in fashion design, as a starting reference to optimize clothes to a specific type of body shape. Adapting this concept to our models allows us to tailor how we utilize blend shapes based on the input body dimensions.

Using the measurements from Figure 1 and adapting the body shape parameter results in the differences shown in Figure 3. As only the body shape differs, the change leads to a more substantial contrast in the chest region, accompanied by a smaller variation in the pelvic area due to the reduced span between the waist and hips. For instance, the avatar in Figure 3b shows how the chest region narrows, whereas the pelvic area widens, leading to its triangular shape. Comparing the hourglass avatar in Figure 3e to the rectangular shape in Figure 3d, the hourglass-shaped avatar possesses both a wider chest and pelvic area, creating a distinct sharp and straight gradient extending from the waist. The optimizations for each body shape type are designed by utilizing blend shapes that impact the entire structure of the core body, ranging from the chest to the hips and thighs.

There are also differences in weight and fitness between various body shapes, with weight gain or loss having unique effects depending on the general body shape.

Individuals with a circular body shape will experience more weight gain around their waist. In contrast, those with a triangular body shape will notice greater increases in their lower waist and hip area. These differences are reflected by incorporating a final fullness slider that adjusts the body shape, ranging from a more fit representation to a more curved and full-body type. This enables operators to create models that accurately reflect the individual's desired appearance based on their specific body shape and weight distribution.

A3Cplus offers comprehensive customization options for the most prevalent body shapes, including circle, triangle, inverted triangle, rectangle, and hourglass. These shapes can be selected through a shape selection interface, as shown in Figure 1. In cases where an operator is unsure which body shape to select, they can cycle through the options until they find a visually suiting match.

3.4 Model Export

A3Cplus's export process is another major aspect, setting it apart from the existing tools. Conventionally, as explored in Section 2, tools require an export of the entire 3D model to a file to then import them into another application. While it is possible to export a complete model with applied blend shapes to the GL Transmission Format (glTF) file type in A3Cplus, it is not the recommended method as it requires the export of large files and an overall fragmented user experience. As the base model is generic and already contains all the potential positions that can be generated in the tool, exporting entire models would be space inefficient and more challenging to deal with in other software. Since the base model is designed to handle a wide range of blend shape possibilities, exporting the entire model is unnecessary or inefficient when only blend shape values need to be modified.

Since we are only modifying blend shape values, we can avoid the model exporting process altogether and save the blend shape values in more widely used interchange formats like JSON. This approach also makes it easier for users to work with the output in their 3D applications, as they can import and optimize the same model as seen in our tool into their editors. Editing their environments using the same model enables the developer to test their 3D environment with any potential blend shape combinations, guaranteeing that their program will always work. In addition, game engines such as Unity or Unreal do not support importing model files during runtime natively as their importers are part of their Editor code base, having to then rely on 3rd party importers.

Building on this point, exporting and manually managing the file still adds friction and the potential for human errors. As we simply want to pass the values into a different program, we do not have the requirement of storing any of the resulting outputs. To streamline the blend shape value use with A3Cplus, we developed a feature that enables the direct transfer of blend shape values into a custom target binary. This eliminates the need for manual file management, significantly reducing the potential for human error and further enhancing the user experience.

(a) Circular. (b) Triangular. (c) Inverted triangular. (d) Rectangular. (e) Hourglass.

Figure 3: A3Cplus output examples of different body shape types based on identical measurements.

4 DISCUSSION AND FUTURE WORK

The proposed tool's novel structural components leverage an artistically designed off-the-shelf base model to efficiently create anatomically accurate avatars based on phenotypic measurements.

A3Cplus fulfills the initial requirement by being capable of dynamically adapting avatars to the user's body in real-time, both during creation and runtime. In addition to automatic rigging, it enables the possibility of making real-time adjustments to its blend shapes in the editor and within game engines. Results are deterministic within a specified tolerance, i.e., by inserting the same input values, the output model remains consistent throughout each run.

A3Cplus also fulfills the inclusivity requirement for all involved parties, from developer to operator and user. Firstly, by constituting a low cost and a minimal space requirement, the tool provides a low barrier to entry for realistic full-body illusions. Furthermore, we have shown its advantages in development by incorporating an easy-to-use interface and simple connectors into game engines using command-line arguments. This makes it effortless for developers to create applications that require full-body illusions. The intuitive user interface simplifies the process of creating avatars, allowing users to customize their full-body illusions easily in a matter of seconds. Whether the user is used to the tool or just starting out, A3Cplus makes creating realistic and engaging full-body illusions for various applications effortless. Lastly, by prioritizing accessibility, our tool accommodates individuals who would not be able to take part in active scanning processes due to physical limitations or anxiety around scanners or confined spaces, providing full-body illusions accessible to anyone.

Regarding the final privacy requirement, we prioritized minimizing data use throughout the entire life cycle of the process. We mitigate contemporary privacy concerns by not utilizing photographic information and external online platforms for our tool's operation. If the final VR application does not store blend shape values, our tool allows privacy-conscious individuals to utilize it directly without disclosing their body measurement data to the operator, as the tool does not store but passes on the blend shape values to the application.

Although A3Cplus already aligns with our introduced primary requirements, several areas remain that require further attention, particularly for aspects such as the quality of the output. In its current state, the tool operates under various assumptions that do not accurately reflect reality, such as generating symmetrical bodies and focusing uniquely on adults. Additionally, currently predefined skin textures are used, i.e., visual features such as differing pigments, scars, and birthmarks are not accounted for, which can influence realism.

Introducing these elements into the user interface is complex, as it could overwhelm an average user. Another limitation is the inability to modify the head or facial features of the avatar, restricting its applicability to an egocentric perspective where users cannot view themselves in a mirror above the neckline. Lastly, as our blend shape modifications are primarily based on common artistic or fashion-based interpretations rather than scientific data, we cannot be certain that every type of body shape is represented authentically. The limitations conflict with creating a simple user experience to create avatars for full-body illusions. We will address these issues in future work and explore further user interface options that allow more complex behavior to be seamlessly integrated.

5 CONCLUSION

This paper presents A3Cplus, a tool for efficiently creating anatomically accurate avatars for clinical and therapeutic VR applications and avatar-based immersive applications in general. In particular, A3Cplus streamlines the creation process and provides an easy-to-use, secure, and offline workflow that helps generate realistic avatars without the need for complex scans and measurements. During the process, a base avatar is adapted with blend shapes by phenotypic measurements with a set of fundamental body types. The results can be easily exported and integrated with other tools, engines, or content creation pipelines.

A3Cplus is already employed in ongoing VR-based psychological studies to help experimenters quickly create realistic, morphable participant representations. Although the tool already satisfies the core requirements and produces sufficiently detailed avatars for VR applications in therapeutic or clinical contexts, several limitations and potential improvements in terms of user experience remain. We plan to address these and further refine the software to soon make it available as a free and open-source resource for researchers.

Generally, A3Cplus is not limited to VR scenarios but can also be used in less critical, non-therapeutic contexts where simple yet anatomically accurate avatar creation is desired, such as in games, digital fashion stores, or computer-aided design.

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