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Exploring the Perception of Center of Mass changes for VR Avatars

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Figure 1: *3D models of the 8 actors used in Experiments 1 and 2, depicting walking and jogging motions. The models represent varying body mass indices (BMI), with half in the high BMI group and the other half with low BMI. Left: High BMI M/F and Low BMI M/F walking; Right: High BMI M/F and Low BMI M/F jogging*

Abstract

Populating Virtual Environments with animated virtual characters often involves retargeting motions to 3D body models with differing shapes. A user's avatar, for example, should move in a way that is consistent with their model's body shape in order to maintain the sense of presence. We present a set of perception experiments to explore how motions captured from actors with various body mass indices (BMI) are perceived, when they are retargeted to characters with different BMIs. We also explored the perceptual effects of retargeting average and physics-based motions. To explore the latter, we devised a physics-based controller framework that utilizes motion, target body weight, and height as inputs to generate retargeted motions. Despite the controller generating varied motions for various body shapes, average motions consistently outperformed the controller-generated motions in terms of naturalness. Overall, this work highlights an anthropometric based physics controller and a novel approach for perceptual evaluation of human motion retargeting for virtual characters.

CCS Concepts

• ***Computing methodologies*** → ***Perception; Physical simulation;*** *Virtual reality;*

1. Introduction

Virtual characters can now be found in a wide variety of applications, such as video games, virtual assistants, and virtual reality experiences [LBS13]. However, creating realistic and responsive virtual characters remains a key challenge [LC21] in virtual reality scenarios. To this end, motion capture technology is often used to capture the motions of human actors [Men00, GY03]. The captured motion is often retargeted to a virtual character model that has a different body shape than the original model [Gle98]. In a virtual environment, humans can be very sensitive to even the slightest discrepancies in movements with which they are very familiar, e.g., walking [Joh73, JT03]. Therefore, retargeting may influence the perception of observers due to the dynamic properties implied by a character's shape, which often differs from that of the original actor [Tro13].

The main goal of our paper is to provide a novel approach for the perceptual evaluation of human motion retargeting to bodies with different shapes. To represent body shape, we have used the Body Mass Index (BMI) metric, which is used by the World Health Organization to classify individuals as underweight (BMI < 18.5), normal weight (BMI 18.5–24.9), overweight (BMI 25–29.9), or obese (BMI > 30) [O*95]. The MoSh++ method [MGT*19] and statistical body model SMPL-X [PCG*19] were employed to generate realistic low and high BMI body shapes and their associated motions, based on real actors.

We used our approach to study the perceptual effects of matching inconsistent body shapes and motions, and of changing a character's center of mass (CoM) based on anthropometry (i.e., the study of human body measurements), using a physics-based controller.

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In Experiment 1, we assessed the perception of consistency in walking and jogging animations where the original body shape and motion matched or mismatched. Ratings varied based on body shape, motion, gait, and sex depicted, which implies that certain body characteristics and motion styles may have influenced ratings.

For Experiment 2, we developed a physics-based framework using motion, target body weight, and height as inputs for retargeted motion. We wish to know if postural control parameters, i.e., mass and inertial properties like CoM location, can generate realistic motions across different BMIs. This was achieved by controlling limb balance points in our physics-based approach. For this study, average male and female motions from 15 actors were used, as such motions have been found to be most attractive and least distinctive [HRZ*13]. However, we found that unmodified average motions were generally perceived as more natural than physically modified ones, with some variations related to gender. The underlying reasons for these differences between genders require further investigation. Our findings suggest that achieving natural motion for a specific BMI model requires consideration of factors beyond postural control parameters. Future research needs to explore additional physiological factors or employ more complex controller models to enhance motion realism.

2. Related Work

Human Locomotion & Gait: While basic locomotion such as walking has long been a feature of graphics applications, replicating the wide variety of human walking styles is still an open challenge. Human gait analysis has been a very active area of research, mainly in health [VCS18, MDLHGZMZ14, JPL*18], sports [ZGZ19, EHB18] and identification [NBN19, WWP18]. Many factors influence human gait, with the most significant being demographics, body mass index (BMI), and sex [CAF17]. A change in BMI also changes the mass and corresponding inertia in all body segments, thereby causing variations in movement and ground reaction force effects [BK07, DPPSRJ12]. The location of the Center of Mass (a.k.a. center of gravity [HK06]) is critical for describing gait features [JWIG93, HWF*98]. Various anthropometric tables have been compiled to estimate the CoM location in different body segments along with their mass distribution [Win09, MCC*80, YCS*83]. We used these inertial parameters in our physics-based motion retargeting framework.

Body Shape & Appearance: McDonnell et al. [MJH*07] ran a study to explore the effect of body model (male, female, neutral and point-light) and motion on the perceived sex of virtual characters and found that both the model appearance and motion were important. Johnson and Tassinary [JT07] reached a similar conclusion, i.e., that both appearance and motion information played a role when participants judged attractiveness. These results demonstrate that the influence of body shape on the perception of human motion should not be overlooked.

There have been recent advancements in statistical body models for generating realistic body shapes. Shi et al. [SOWO17] presented a data-driven approach to generate varied body shapes and performed a perceptual study of the relationship between body shape, attractiveness, and distinctiveness for median height and girth bodies. A skinned vertex-based model called Skinned Multi-Person Linear eXpressive (SMPL-X), which represents a wide variety of body shapes in natural human poses, was presented by Pavlakos et al. [PCG*19]. This body shape model is compatible with existing rendering engines and graphics pipelines. For this paper, we used the MoSh++ method introduced by Mahmood et al. [MGT*19], which directly fits parametric body models such as SMPL-X to 3D motion capture markers. The method can recover body shape and 3D pose with high accuracy, thus allowing us to create our virtual characters with varied body shapes (see Figure 2).

Applied Perception: Over the years, extensive research has been conducted on the perception of biological body motion. In early work, Johansson [Joh73] presented biological motion as arrays of point-lights moving across a high-contrast screen. It was also demonstrated that familiar motion, e.g., a friend's walk, can be identified from these point-lights [CK77]. Later, Troje et al. [Tro02] developed a framework to retrieve information from biological motion patterns using gender classification as an example.

Jokisch and Troje [JT03] added another dimension by showing that biological motion can be a cue to estimate the size of walking creatures. Furthermore, Jain et al. [JAA*16] found that viewers can distinguish if a motion is performed by a child or adult for the same action. These studies showed that humans can perceive the identity, age and gender of actors performing diverse actions, highlighting the significant influence of motion style on perception. Niay et al. [NOZ*20] demonstrated that observers could select the preferred walk ratio of virtual characters within the range established by existing literature, further emphasizing the high sensitivity of humans to subtle variations in walking animations. However, Kenny et al. [KMH*19] found that inconsistent body shape and motion during interactions with objects were harder to detect.

Meanwhile, Klüver et al. [KHT16] investigated perceived attractiveness by manipulating internal consistencies in anthropometric and kinematic cues of biological human walkers. Notably, they found a significant link between internal consistency and sexual attractiveness. Similar investigations by Hoyet et al. [HRZ*13] explored the distinctiveness and attractiveness of motions and demonstrated that viewers can distinguish between different actors while performing the same motion, emphasizing the remarkable capacity of humans for differentiating biological motions. Recently, Russell et al. [RSM*22] investigated the ability of observers to detect inconsistencies between shape and motion and found that detection rates were low, except in the case of walking motions. Unlike previous work, we employ a motion database featuring multiple female and male actors, each performing both activities at the same speed. Additionally, we delve into the impact of additional physical parameters on perception in this context.

Motion Editing is a commonly used technique for introducing variation in locomotion animation. Le Callennec and Boulic [LCB06] developed a constraint-based editing tool that enables animators to modify existing motions. This tool provides a user-friendly interface for animators to manipulate and refine motions according to their specific requirements. Ahmed et al. [AMH01] employed time warping and PCA for motion generation using pre-captured motion data, while Glardon et al. [GBT04] applied Principal Component Analysis to produce lower dimensional motion data for generating new walking patterns. The framework presented by Multon et al. [MKHK09] can synthesize new motions with morphological adaptations along with kinematic and physically based corrections. Learned motion manifolds were employed by Holden et al. [HSK16] to generate human motion by combining hidden units of a convolutional autoencoder. Many motion editing techniques demand ample motion data or manual constraint adjustments. This reliance on data availability or manual intervention can restrict the efficiency and adaptability of such methods.

Physics-based Character Animation: Physics-based character animation is a promising approach for generating realistic and plausible character movements. For example, Faloutsos et al. [FVdPT01] used composable controllers to synthesize basic actions such as balance, arm reactions, and recovery from perturbations. By combining these controllers, their framework could generate complex and realistic character animations.

In the work by Martinez et al. [MNMO08], particle filters constrained by human physiology were used for tracking different parts of the human body. By tracking and replicating the motion, a simulated character could assume the same pose and perform similar actions as their human counterpart. In a hybrid approach, Alvarado et al. [ARC22] combined kinematic constraints and lightweight physics, thereby giving valuable insights into enhancing interactive character creation through physics-based characters. Liu and Hodgins [LH17] employed a deep Q-learning algorithm to learn schedulers capable of designing control systems for dynamic behaviors. This algorithmic approach enabled the generation of sophisticated character animations.

Motion adaptation based on character body type has also been explored. Lyard and Magnenat-Thalmann [LMT08] proposed a space-time optimization approach and a variant of the Normalized Radial Basis Function (NRBF) to fit motion to different body types at runtime, while Al-Asqhar et al. [AAKC13] presented a framework for interactive motion adaptation that could handle significant deviations in mesh structure and character morphology. Al Borno et al. [ABRB*18] developed a novel space-time optimization-based physical controller that learned how to adapt to different body shapes and constraints. While most of these approaches are primarily focused on handling the controller to achieve physical plausibility, we aim to adapt motion after the controller process by altering the inertial properties.

3. Experiment 1: Shape and Motion

This experiment aimed to study how inconsistencies between body shape and motion affect human animation perception. While previous research by Russell et al. [RSM*22] showed limited detection of such inconsistencies in most motions, they were more noticeable in walking motions. Our study builds on this by exploring the relationship between body shape and motion perception, focusing on walking and jogging motions at consistent speeds across actors. Participants were tasked with rating body shape and motion consistency using a 5-Point Likert Scale. We hypothesized that participants would rate consistent animations higher for both gaits and expected similar ratings for motions within the same BMI group.

3.1. Method

Stimuli: Motion and marker data were taken from the dataset described by Hoyet et al. [HRZ*13], comprising 15 male and 15 female actors with diverse motions and BMI values. Walking was recorded at a frequency of $\approx$ 112 steps per minute, while jogging was at $\approx$ 138 steps per minute. We selected four male and four female actors, evenly distributed between low and high BMI groups. We aimed to maximize weight differences while maintaining the same height within BMI groups (see Appendix A for details).

Our stimuli creation followed methods from previous studies [KMH*19, RSM*22]. We employed the MoSh++ method [MGT*19] and SMPL-X statistical body model [PCG*19, RTB17] to generate body shape and motion. MoSh++ produced a 3D surface with 10,777 triangles, which we converted to a *C#* readable format using the bmlSUP Unity Player [BTT21] for animation playback in Unity. For the "consistent" stimuli, we directly used the original actor's body shape and pose, while for the "inconsistent" stimuli, we swapped body shape values between actors while keeping the motion identical, as shown in Figure 2. We repeated this process for all the actors' motion for both gaits (i.e., walking and jogging). The animation clips were rendered in Unity, featuring a treadmill in an empty environment with a simple checkerboard texture to prioritize realism over detailed skin textures and avoid the uncanny valley effect [SWH18, MMK12].

Participants: Sixteen volunteers (8F, 18-60+) from a variety of backgrounds participated in the online survey. None had previously participated in the motion capture sessions for stimuli creation. Recruitment occurred through email lists and social media. The experiment was conducted using Qualtrics, ensuring fully anonymous results. Participants provided informed consent before the experiment and could optionally provide demographic information.

Procedure: The study employed a mixed design to investigate the impact of the between-subjects factor "SEX" (of the actors) and within-subjects independent variables: GAIT (i.e., of the actor either walking or jogging), BODY (i.e., the BMI of the actor with the displayed model), and MOTION (i.e., the BMI of the actor with the displayed motion) on consistency ratings. Participants were assigned in a counterbalanced manner to male or female groups to ensure an equal number of responses for each sex. Within each sex group, participants viewed animations representing combinations of 2 GAIT types (Walk or Jog) X 4 BODY types (high BMI Hi1, Hi2, low BMI Lo1, Lo2) X 4 MOTION types (high BMI H1, H2, low BMI Lo1, Lo2). Within each sex group, participants watched two blocks of animations, with the order of GAIT (walk or jog) randomized.

Within each block, videos were shown in random order. Before each GAIT block, participants viewed example stimuli of consistent and inconsistent animations for practice, featuring actors with different BMIs. These examples were not used in the actual experiment. Each GAIT block included 16 distinct videos: 4 BODY x 4 MOTION (1 consistent, 3 inconsistent), each repeated twice (and later averaged). Therefore, each GAIT block consisted of 32 questions, with each video lasting 4 seconds. The 4 seconds duration allowed two full gait cycles to be shown, and participants were allowed to play the video again if needed. The total duration of the experiment averaged approximately 20 minutes. During the experiment, participants rated motion consistency with body shape on a 5-point Likert scale, ranging from "Very Inconsistent" to "Very Consistent." They proceeded to the next video clip by clicking the "Next" button after providing their ratings, which only appeared after viewing the clip at least once.

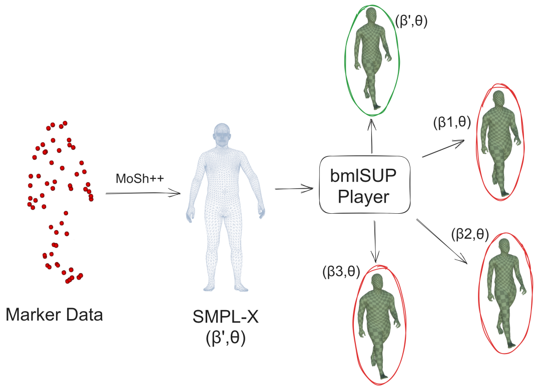

Figure 2: *Experiment 1 Stimulus Generation Process: shape (β) and pose (θ) parameters are extracted from marker data using MoSh++ (green: consistent motion; red: inconsistent motion)*

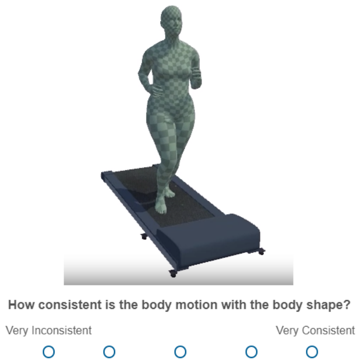

Figure 3: *Experiment 1 example stimulus: Body shape and motion were varied across trials to investigate the effect of inconsistencies*

3.2. Results

After confirming the normality of the data (normal p-plots and distribution fitting), we conducted a mixed ANOVA to investigate the effects of between-subjects factor SEX and within-subject factors GAIT, BODY, and MOTION on participants' ratings of consistency. For every main and interaction effect, we conducted post-hoc analysis using Tukey's tests to find significant differences between all possible pairs of means. We only report significant effects with $p < 0.05$ throughout. The results of the analysis, presented in Figure 4, revealed several significant main and interaction effects. Please refer to Appendix A for detailed results.

The significant main effect of GAIT ($F(1,8) = 8.11, p < 0.01, \eta^2 = 0.37$), was observed because participants rated walking motions as more consistent overall than jogging motions, as confirmed by post-hoc. The effect is further explained by the two-way GAIT × SEX interaction effect ($F(1,8) = 6.05, p < 0.05, \eta^2 = 0.30$) as only female walking motions were rated higher than the female jogging motions. Moreover, a three-way GAIT × BODY × SEX ($F(3, 8) = 4.99$, $p < 0.001$, $\eta^2 = 0.26$) interaction effect was also found, and post-hoc analysis showed that female low BMI bodies received higher ratings for both gaits, while no such trend emerged for males. We can also see that there was a significant main effect of BODY ($F(3,24) = 2.89, p < 0.05, \eta^2 = 0.17$), caused by participants rating animations of the low BMI body Lo1 significantly higher than the high BMI body Hi1, as confirmed post-hoc. Post-hoc analysis on the two-way BODY × SEX interaction effect ($F(3,8) = 11.84, p < 0.001, \eta^2 = 0.46$) indicates that although female stimuli with low BMI bodies were rated higher, male stimuli with the Hi1 high BMI body received the highest ratings on average. The interaction effect of BODY × MOTION ($F(9,24) = 2.59, p < 0.01, \eta^2 = 0.16$) shows a preference for similar BMI of body and motion, except for the low BMI body (Lo2) that received higher ratings for different BMI motions, including the Hi1 motion.

Lastly, the three-way interaction effect of BODY × MOTION × SEX ($F(9,24) = 6.41, p < 0.001, \eta^2 = 0.31$) indicates that all female bodies with low BMI were rated higher, regardless of the type of motion. For males, a similar but weaker trend was observed, only for high BMI bodies. These findings highlight the complex interactions between multiple factors and their influence on participants' ratings of motion consistency. The effect sizes (η^2) were moderate to large, indicating a substantial impact of the independent variables on participant ratings.

Discussion: Based on Russell et al.'s prior research [RSM*22], we initially expected participants to recognize consistent motions, where body shape matched the motion. However, Figure 4 illustrates that the results did not support this hypothesis; only a minority of participants rated consistent motions more highly. Nonetheless, the two-way interaction between BODY and MOTION indicated that ratings were influenced by both body shape (low or high BMI) and the type of motion (consistent or inconsistent). Post-hoc analysis revealed that participants tended to give a higher rating to body shapes that were in the same BMI group as the actor who performed the displayed motion. For instance, if the motion featured an actor with a low BMI, participants were more likely to rate body shapes within the low BMI group as more consistent compared to those in the high BMI group. This underscores the significance of congruence between body shape and motion in participant ratings.

The influence of GAIT and SEX on participant ratings was more prominent. Participants could readily differentiate between different gaits for both sexes, likely owing to distinct expectations and perceptions linked to these categories. This finding aligns with earlier studies by Troje et al. [Tro02] and Niay et al. [NOZ*20], which similarly highlighted the significance of dynamic information and motion style in perception. Notably, specific female body shapes, particularly those with low BMI (Lo1 & Lo2), consistently received higher ratings from participants. This suggests that certain physical attributes significantly influence perceptions of attractiveness. This observation aligns with prior research by Thaler et al. and Troje [TBM*20, Tro03], which emphasized the role of sexual dimorphism in walking on female attractiveness. Our results support this idea, indicating that the physical characteristics exhibited in body shapes during walking have a substantial impact on perceptions of attractiveness in females.

Our findings suggest that distinct factors may influence different perception attributes in these animations. While we primarily focused on BMI in this study, which includes body weight and height, it directly corresponds to various physical aspects of the human body, such as body mass, velocity, and gravitational effects. Thus, we concentrated on modeling the physical aspects of the human

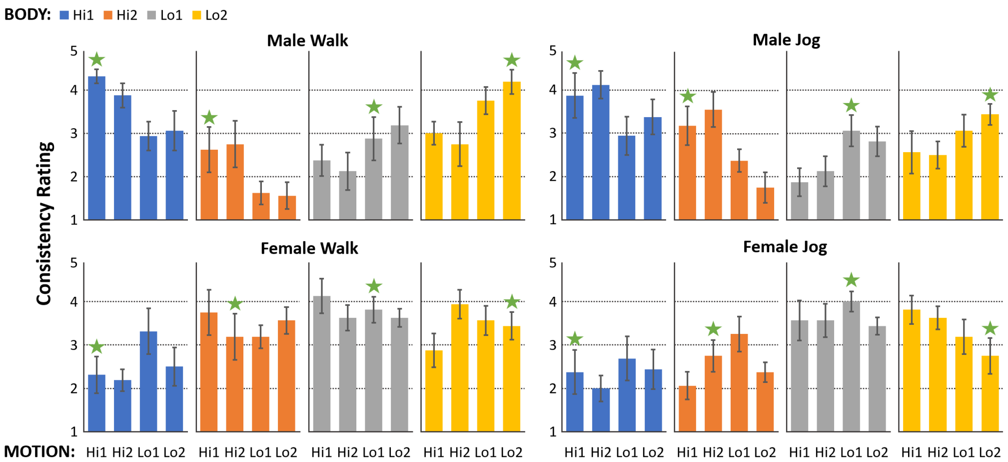

Figure 4: *Experiment 1 Results: Mean rating scores for varying BMIs. Higher scores indicate more favorable ratings. Consistent motions, i.e., where the original body shape and motion match, are marked with a star. Error bars show +/− standard error*

body and assessing their impact on motion perception. However, it's important to acknowledge that there are other biological factors like muscle-tendon activation, the role of fat, and various other considerations that were not addressed in this work.

4. Physics-based framework

Experiment 1 demonstrated that motion style has an influence on the ratings of consistent & inconsistent motions in some scenarios. We next wished to investigate the relationship between human motions and body shapes further, and in particular to assess the effect of physical properties on this relationship. To this end, we developed a physics-based framework that would allow us to control the motion of a particular body using physical parameters, which we evaluated afterwards in a second experiment.

Since the laws of physics exist in nature, human perception and understanding of the virtual world are heavily influenced by these physical laws. The presence of responsive characters is very important for a truly immersive virtual experience [LC21] [LBS13]. We present a Balance Point Controller that adapts a motion based on the character's physical attributes like body weight and height and works with game engine pipelines such as in Unity 3D. The framework combines kinematics and dynamics, and as a result, adapts a motion based on a character's body shape. A reference motion is given as input along with the target body weight and height and a physics-based character is constrained to follow the reference motion. The user-defined parameters of height and weight alter the inertial properties of the character, which in turn generate a new adapted motion.

4.1. Physics-based Character

The character model implemented in the Unity™ game engine consists of a humanoid skeletal structure with a body mesh and features 22 Degrees of Freedom (DoF) and 10 joints. The *ragdoll* model uses capsule or cuboid shaped rigid bodies for the major limbs, along with a sphere for the head, as depicted in Figure 5. Rigid body mass distribution aligns with anthropometric principles

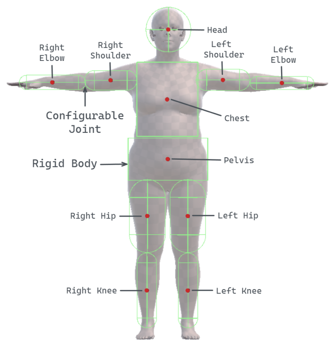

Figure 5: *Ragdoll model with colliders, rigid bodies, and configurable joints in body segments*

as discussed in Section 4.2. Each DoF represents the relative rotation or translation of connected body segments via revolute or prismatic joints, realized through configurable joints in Unity. We implemented a PD controller, a feedback control system used for system stabilization and error reduction in engineering. It combines proportional and derivative terms in the control law:

$$\mathrm{u(t)} = -k_p(e(t)) - k_d\dot{e}(t)$$

Here, $u(t)$ represents the control signal, $e(t)$ denotes the error between desired and actual states, and $\dot{e}(t)$ is the error derivative. k_p and k_d are proportional and derivative gains, determining each term's contribution. While stable PD controllers are available [TLT11], we opted for the traditional controller for more control over the character.

The PD controller calculates control forces and torques in every time step for every joint to move the *ragdoll* from its current pose to a target pose. Joint torques τ are computed as:

$$\tau = -k_p(\mathbf{q} - \bar{\mathbf{q}}) - k_d\dot{q}$$

Here, $\mathbf{q}$ represents the current posture, $\dot{q}$ is the velocity, and k_p and k_d are the proportional and derivative gains. Gain values are determined through a combination of trial and error and optimal control techniques. For further details, refer to Appendix A.

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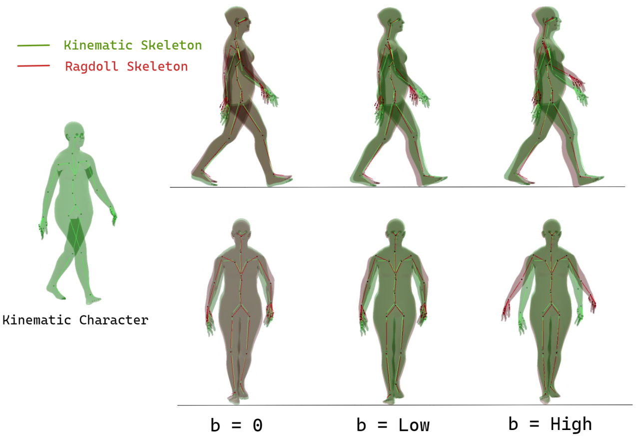

Figure 6: *Effect of Balance Control factor on the posture*

4.2. Balance Point Control

Stability in character animation is crucial for realism, with the center of mass (Balance Point) serving as a key factor. Each rigid body within the *ragdoll* model corresponds to a hierarchical structure mirroring the skeleton, with the pelvis at the top influencing all sub-branches.

Anthropometric data from sources like McConville et al. and Young et al. [MCC*80, YCS*83] guide the mass distribution within body segments and the longitudinal shift of the center of mass. The center of mass position isn't precisely at the geometric center but varies based on factors like segment length and mass.

Using this anthropometric data, we calculate each rigid body's weight in the N=11 *ragdoll* by multiplying the total body weight **W** by X_w. The new center of mass position for each segment is determined by multiplying segment length l_i by X_l.

We introduce the balance control factor **b** to measure the change in the overall center of mass position:

$$b = |C - C'|$$

Where **C** is the original center of mass position, and **C'** is the updated position:

$$C = \sum_{i=1}^{N} c_i m_i \div \sum_{i=1}^{N} m_i$$

$$C' = \sum_{i=1}^{N} c_i' m_i' \div \sum_{i=1}^{N} m_i'$$

Here, $c_i' = c_i + (l_i \times X_{l_i})$ and $m_i' = W \times X_{w_i}$. c_i represents the center of mass position, and m_i is the mass of the i_{th} rigid body.

Figure 6 illustrates the impact of the balance control factor on skeletons. At **b**=0, the ragdoll closely mirrors the kinematic character. A small **b** (Low) results in subtle center of mass shifts and posture differences. A higher **b** (High) causes significant shifts and pronounced posture changes. This varying **b** offers flexibility in achieving different levels of realism and fidelity in ragdoll motion.

4.3. Testing and Validation

We assessed the physics-based framework by inputting character models with varying body weights and heights, comparing the results with data from studies on real human walking gait analysis. As MacLean et al. [MCM16] noted, there are significant lower-body extremity differences among different BMI groups. The results, shown in Figure 7, were time-normalized to 100% of the gait cycle and demonstrated variability across characters with different body dimensions.

Due to balance point control, the pelvis trajectory differs for each character (depicted in Figure 7 - left). The total body mass significantly influences the position of the center of mass (CoM) of the pelvis. The diverse BMI of characters affects the CoM position. Knee extension moments during one gait cycle vary among different BMI characters (Figure 7 - middle). The left knee moment values (N-m) are normalized and plotted, showing consistent differences between higher and lower BMI characters, in line with MacLean et al.'s findings [MCM16]. However, absolute peak values for higher BMI individuals do not precisely match those reported in biomechanical research [BK07, MCM16, BMMA*17]. Figure 7 (right) displays normalized knee flexion values (°) for the left leg. Characters with higher BMI exhibit lower flexion, indicating the impact of additional mass. These patterns align with the previous work as shown in Figure 7 (Black & White).

Upper body parameter analysis is limited due to the scarcity of literature in this specific area, particularly regarding arms and head. Nevertheless, prior studies have demonstrated that the lower-limb and trunk model effectively captures the overall body center of mass kinematics with minimal errors [HMF18, VGRL10]. This suggests that lower limb and trunk regions have a more significant influence on center of mass properties.

Balance point control produces distinct and comparable gait patterns across characters with varying body dimensions [SUM19], validated through comparison with real human gait analysis data. Overall, this method yields promising results, which are further evaluated in Section 5. This method is referred to as COM from here on.

5. Experiment 2: Physics and Average Motion

Once we had developed the COM framework for modifying the physical properties of a given motion, we ran a second experiment to determine whether it was effective at generating motions that were consistent with the displayed bodies. We achieved this by comparing COM-retargetted motions with more natural average motions, side by side.

5.1. Method

Stimuli: To ensure consistency between the experiments, we selected the same actors for the body shape parameters. Each video clip, presented from a third-person perspective, featured two moving bodies displayed side-by-side on the same screen. Participants were tasked with selecting the motion they perceived perceived more 'natural', where 'natural', which was explained to them as follows: "*Sometimes, the motion quality will be good and will match the BMI well, (i.e., it will look more natural). Other times,*

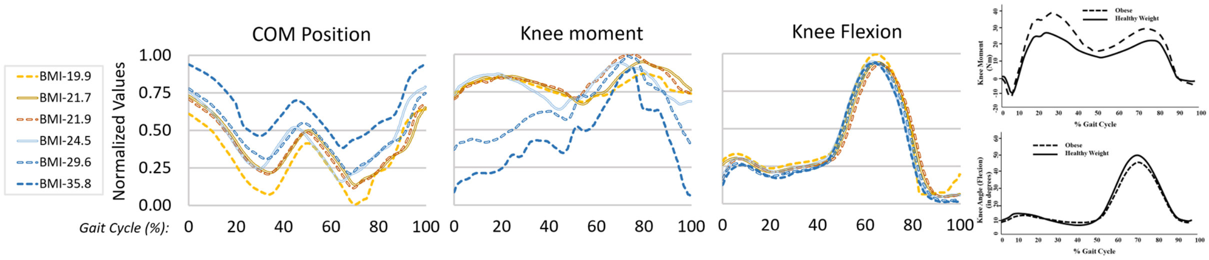

Figure 7: *Comparison of biomechanical parameters across characters with different BMIs for one complete gait cycle – i) Root CoM (Center Of Mass) Position: normalized position for the level of displacement; ii) Knee Moment: normalized values of the Knee extension moment; iii) Knee Flexion: Normalized values of Knee flexion angle; iv)The baselines for Knee moment and v) Knee flexion values [MCM16] [BMMA*17]*

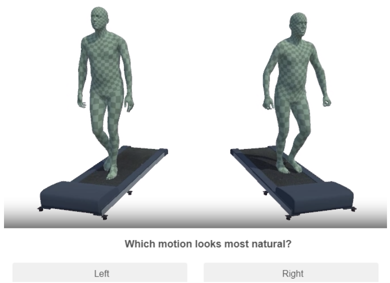

Figure 8: *Experiment 2 example stimulus: Two motions were presented on the same body and participants selected the one they found more natural.*

the motion quality may be bad, or it may look like the motion should be for a higher or lower BMI (i.e., it will look less natural)."

As the results of Experiment 1 indicated that motion style may have significantly affected the ratings of consistency, we controlled for this effect in this study by using the average motions from a previous study conducted by Hoyet et al. [HRZ*13]. These motions were generated from same dataset as used in Experiment 1 (Section 3), using Dynamic Time Warping, a technique employed to align and derive the average motions of multiple actors. Separate average motions were created for each male and female walk and jog gait.

These average motions were then displayed side by side with motions that were retargetted using our COM method. To generate these retargeted motions, we adopted the methodology outlined in Section 4.2, utilizing the SMPL-X body models. In Unity, the average motion was rendered using the SMPL-X Unity plugin, employing the normal unity animation system. For the physics-based retargeting method, we utilized the dual-rig approach to render the animation. The average motion was played normally in the animation system, with the mesh renderer turned off (master rig). Subsequently, a ragdoll with the same mesh was created to follow the movements of the master rig. To generate the retargeted motion on top of the average motion, the weight and height of the actors were manually inputted.

Participants: We recruited sixteen new volunteers (5 female, ages 18-60+). None of these participants had prior involvement in Experiment 1 or the motion capture sessions used to create the dataset. We employed recruitment through email and various social media platforms, targeting individuals from diverse backgrounds. We administered the experiment using the Qualtrics platform, maintaining consistency with the previous study. Before participating, all volunteers received and voluntarily signed an informed consent form. They also provided the requested demographic details.

Procedure: The experiment employed a within-subject design, enabling participants to assess all combinations of independent variables: GAIT, SEX, BODY, and METHOD. Each trial featured animations representing 2 GAIT (Walk or Jog) × 2 SEX (Male or Female) × 4 BODY shapes (high BMI H1, H2, low BMI L1, L2) × METHOD motions (No COM or COM). We organized the experiment into two blocks based on *SEX* (Male and Female), with sub-blocks for *GAIT* (Walk and Jog). Block and animation sequences were randomized to ensure variability and prevent order effects. Before each *SEX* block, participants viewed subjects' body shapes in increasing BMI order for familiarization. Four practice videos were shown before each main block, distinct from the actual experiment. In stimuli, the two *METHOD* motions were presented side-by-side on matching body shapes, allowing for direct motion comparison. The motion's position (left and right) was counterbalanced. Each gait block included 8 unique videos (4 *BODY* types × 2 sides) shown twice randomly, resulting in 16 questions per block. Video clips lasted 4 seconds each. In total, there were 4 blocks (2 *SEX* and 2 *GAIT*), making the experiment last approximately 12-15 minutes. Participants viewed video clips and selected the more natural motion between the left and right sides, as shown in 8. They indicated their choice (left/right) after viewing the clip at least once, enabling an informed decision before proceeding.

5.2. Results

We conducted a repeated measures ANOVA to examine the effects of GAIT, SEX, BODY, and METHOD on participants' ratings of naturalness. Please refer to Appendix A for detailed results. The main effect of METHOD, comparing the retargeted motion to the average motion, was found to be significant ($F(1,65) = 65.00$, $p < 0.001$, $\eta^2 = 0.81$). Post-hoc analysis revealed that average motions received higher naturalness ratings compared to retargeted motions. However, there were no significant main effects of BODY or SEX on naturalness ratings.

Notably, a significant two-way interaction effect was observed between SEX and METHOD ($F(1,21.36) = 21.36$, $p < 0.001$, $\eta^2 = 0.59$), indicating that the effect of body motions on naturalness ratings differed between male and female animations. Specifically, the COM method showed better performance for females compared to

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males, suggesting that the retargeted motion technique had a larger impact on males. Additionally, there was also a significant two-way interaction effect between GAIT and METHOD ($F(1,6.51) = 6.51$, $p < 0.05$, $\eta^2 = 0.30$). However, post-hoc analysis did not reveal a significant difference between the methods for walking and jogging motions. Overall, these results suggest that the choice of motion retargeting method influenced participants' ratings of naturalness, with the average motion generally being perceived as more natural.

Discussion: The main effect of METHOD significantly influences participants' ratings, indicating a substantial impact on their preferences. The average motion received higher naturalness ratings compared to the retargeted motion, as shown in Figure 9, aligning with Hoyet et al.'s previous research [HRZ*13], where similar results regarding the attractiveness of average motions were reported. The interaction between SEX and METHOD complicates the relationship between motion perception and physical properties. Our proposed COM method performed better for females than males, suggesting differing effects of motion retargeting based on gender, potentially due to body proportions or movement patterns. Similarly, the GAIT and METHOD interaction highlights gait style's influence on ratings, but no significant differences emerged for walking and jogging motions in post-hoc analysis.

Runeson and Frykholm's research [RF83] confirms the ability to detect deceptive performances based on gender-atypical movements, emphasizing human intuitions in assessing naturalness. Overall, the promising performance of the COM method for females suggests potential improvements, but it's essential to recognize the limitations of relying solely on inertial parameters and explore other factors in natural motion representation.

6. Conclusions and Future Work

Previous studies suggest that people can detect mismatches in walking motions [RSM*22]. In this work, we explored the impact of body shape on the perception of virtual character motion. At first, we investigated how people perceive animations where animations derived from actors with different BMIs are applied to characters with varying BMIs. Our findings from Experiment 1 revealed that consistency ratings were influenced by interactions between motion, body shape, gait, and sex, rather than solely motion/shape similarity. Notably, female body shapes with low BMI received higher consistency ratings, which corresponds with research on sexual dimorphism in walking patterns [TBM*20,Tro03]. Other factors such as style, attractiveness, and distinctiveness were identified as potential contributors to perception. To control for these factors, average motions were created for the remaining study, as average motions tend to be rated as more attractive and less distinctive.

We developed a physics-based framework aimed at investigating motion consistency through the modification of postural control parameters, specifically focusing on the CoM. The outcomes of Experiment 2 revealed that, in line with previous research, average motions were perceived as more natural compared to retargeted motions [HRZ*13]. The interaction effect between the character's sex and the motion retargeting method used unveiled a complex relationship, as the COM method seems to work slightly better for females than males, potentially due to variations in body proportions or movement patterns. Experiment 2 demonstrated that modifying

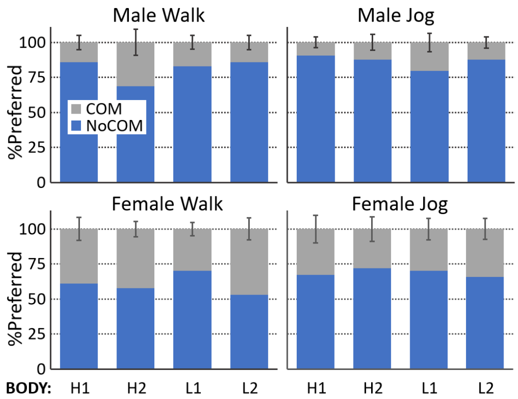

Figure 9: *Experiment 2 Results: Percentage of time the No COM and COM motions were chosen. Error bars show +/− standard error (Note: only one set of error bars is shown, for the COM method, as the standard error is identical for both COM and no-COM)*

motions based on postural control parameters alone does not guarantee shape/motion consistency, which suggests the need to consider additional factors and control parameters.

Our framework offers a valuable starting point for generating natural and realistic human motions. However, it's essential to acknowledge the study's limitations. Firstly, our choice of actors with similar heights constrained BMI variation, particularly for the Hi2 and Lo1 female actors, potentially impacting the results. Future research should address this limitation and comprehensively investigate the interplay between BMI, body shape, motion style, and attractiveness. Additionally, the COM method, relying on inertial parameters for balance point control, shows promise but has its limitations in fully replicating natural motion. We collected participants' comments at the end of the experiments which highlighted recurring keywords, with "Speed" and "Arm movement" being the most frequently mentioned factors. Please refer to Appendix A for a detailed breakdown of comments.

Future work in this area could explore other factors' impact on retargeted motion perception and develop more sophisticated physics-based frameworks. Investigating the influence of factors like gender, race, or age on perception could provide a deeper understanding of retargeting motion across diverse body shapes. While the simple PD controller effectively emulated average motion, a comparative analysis with other controllers like Model Predictive Controller (MPC) [DSAP08] or Linear Time Stable PD controller [YY20] could yield different results and is worth exploring. Such further research into the intricate relationship between body shape and motion perception will enhance the realism and effectiveness of virtual characters across various applications. We will make the complete dataset, including all motion and body shape data used in our research, openly accessible to support future investigations in this field.

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Appendix A: Appendix

Framework Details

In the physics-based framework, we use Unity's built-in 3D physics engine, which integrates NVIDIA's PhysX engine, to retarget motion to different BMI (Body Mass Index) values and modify the CoM. We employ a PD controller that generates forces and torques for the simulation. The simple controller derives forces from the deviation of the current posture from the average motion, while the PD component ensures a smooth emulation of a reference motion on the ragdoll.

Regarding the gain values for the controller, we initially used a simple optimization algorithm to compute estimated values that worked well. Then, we further improved the controller through trial and error. First, we minimized a straightforward objective function, defined as the squared difference between the corresponding angles of the ragdoll motion and the reference motion. After obtaining estimated values, we manually fine-tuned the gain parameters to achieve stable and optimal motion for the base character. The final values of the controller's gain parameters are as follows:

Proportional Torque (k_{p_τ}): 0.16
Proportional Force (k_{p_f}): 30
Derivative Torque(k_{d_τ}): 0.002
Derivative Force(k_{d_f}): 0.01

These gains were obtained to effectively control the limb torques and world forces responsible for driving the base character for averaged motion. When the gain parameters are poorly selected for the base character, they lead to motion divergence, affecting stability and accuracy. The chosen gain parameters work well for all characters, ensuring stable motion. While we acknowledge that other gain configurations might exist, we refrain from changing the gain parameters for COM-modified characters.

Table 1: *Factors to be considered when setting body segment parameters*

Segment	Weight factor(X_w)	COM factor(X_l)
Pelvis	-	-0.088
Head	0.073	-0.034
Spine	0.507	-0.12
Upper Arm	0.026	0.013
Lower Arm	0.016	-0.46
Hand	0.007	-0.32
Upper Leg	0.103	-0.128
Lower Leg	0.043	-0.129
Foot	0.015	-0.051

Table 2: *Attributes of female and male actors used to create stimuli*

	ID	BMI category	Height (m)	BMI
Female Actors	Hi1	Higher	1.60	28.1
	Hi2	Higher	1.64	25.3
	Lo1	Lower	1.60	24.8
	Lo2	Lower	1.60	19.5
Male Actors	Hi1	Higher	1.79	32.1
	Hi2	Higher	1.83	35.8
	Lo1	Lower	1.81	22.7
	Lo2	Lower	1.82	21.7

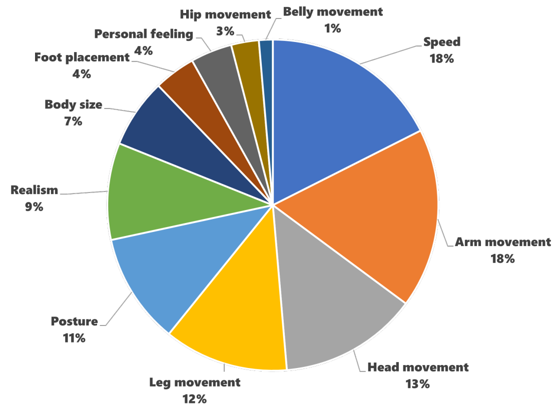

Figure 10: *Factors mentioned in the comments and their frequencies.*

Table 3: *Experiment 1 ANOVA: significant effects for Gait: Walk (W), Jog (J); Body (H1b, H2b, L1b, L2b); Motion (H1m, H2m, L1m, L2m) and Sex (M, F), with effect size (partial η^2), non-centrality (nc) and observed power ($\alpha = 0.05$).*

Effect	**SS**	**dof**	**MS**	**F-Test**	p	η^2	**nc**	**power**	**post-hoc (Tukey),** $p < .05$
Main Effects									
GAIT	3.78	1.00	3.78	8.11	<0.01	0.37	8.11	0.75	W > J
BODY	21.35	3.00	7.12	2.89	<0.05	0.17	8.68	0.65	L2b > H2b
Two-way Interaction Effects									
GAIT*SEX	2.82	1.00	2.82	6.05	<0.05	0.30	6.05	0.63	F/W > F/J
BODY*SEX	87.39	3.00	29.13	11.84	< 0.001	0.46	35.52	1.00	F/L1b > F/H1b, M/H2b, M/L1b
									F/L2b > F/H1b, M/H2b
									M/H1b > F/H1b, M/H2b, M/L1b
BODY*MOTION	21.48	9.00	2.39	2.59	<0.01	0.16	23.29	0.93	H1b/H1m > H2b/L2m
									L1b/L1m > H2b/L1m, H2b/L2m
									L1b/L2m > H2b/L2m
									L2b/H1m > H2b/L2m
									L2b/H2m > H2b/L2m
									L2b/L1m > H2b/L2m
									L2b/L2m > H2b/L1m, H2b/L2m
Three-way Interaction Effects									
GAIT*BODY*SEX	14.52	3.00	4.84	4.99	< 0.001	0.26	14.98	0.89	see discussion
BODY*MOTION*SEX	53.22	9.00	5.91	6.41	< 0.001	0.31	57.69	1.00	and Figure 4

Table 4: *Experiment 2 ANOVA: significant effects for Method: NoCOM (NC), COM (C); Gait: Walk (W), Jog (J); and Sex (M, F), with effect size (partial η^2), non-centrality (nc) and observed power ($\alpha = 0.05$)*

Effect	**SS**	**dof**	**MS**	**F-Test**	p	η^2	**nc**	**power**	**post-hoc (Tukey)**
Main Effects									
METHOD	297896	1	297895	65.00	< 0.001	0.81	65.00	1.00	$NC > C, p < 0.0005$
Two-way Interaction Effects									
SEX*METHOD	45942	1	45942	21.36	< 0.001	0.59	21.36	0.99	$NC*M > NC*F, p < .005$
									$C*F > C*M, p < .05$
GAIT*METHOD	5981	1	5981	6.51	< 0.05	0.30	6.51	0.66	*not sig.*