Real-Time Dynamic Multi-Character Agents

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Figure 1: *Crowds of Bipeds. We can scale various biped parameters, such as leg lengths and body thickness automatically. The figure shows hundreds of balancing characters with a diverse set of scaled character features (e.g., weight, leg-length, height).*

Abstract

In this paper, we present a dynamic, interactive, and controllable 3D biped character technique for creating engaging, life-like, and immersive multi-agent simulations. We accomplish this by exploiting a biomechanically inspired low-dimensional physics-based model that is computationally fast, straightforward, and practical to produce governable, autonomous, virtual avatars that produce human-like balancing biped stepping motions. We synthesize multiple pedestrians that can respond to unforeseen circumstances realistically, such as pushes and trips, while abiding by physically correct constraints (e.g., momentum, stepping dynamics, balancing). Since, in reality, people cannot instantaneously stop and start and possess varying physical attributes (e.g., strength, weight, and height) which our model encapsulates to create customizable life-like avatar movements. We demonstrate our technique through numerous simulations to show the advantages and robustness of our approach for creating adaptive, dynamic, and interactive biped pedestrians with real-time attributes, such as stumbling, navigating by foot placement, and visually plausible character animations (e.g., upper-body posture and intelligent stepping motions).

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Animation I.6.8 [Computer Graphics]: Animation—Types of Simulation–Animation

1. Introduction

Overview: Generating real-time dynamic crowds that are interactive and life-like is interesting, challenging, and important [ZCC*10a, THL*04, TLC02]. Specifically, crowds of humans (i.e., bipeds) embody numerous behavioral attributes (e.g., sad, tired), not including different motions (e.g., standing, walking, stepping) which are enforced by physical constraints (e.g., height, weight, strength). However, of fundamental significance in interactive environments is how to make the pedestrians controllable, adaptable, and responsive, so they can handle environmental disturbances in real-time, such as terrain height changes and push perturbations in a believable way.

Motivation (Interest and Importance): Simulating realistic pedestrians is interesting and important because it allows us to create more captivating, and life-like virtual worlds. We focus on creating crowds of interactive pedestrians that can run at real-time frame-rates, which enables the user to be fully engaged and delighted. We target individual

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agents within the crowd. We focus on making each agents' movements more realistic and physically-correct, more interactive and engaging (e.g., the ability to push and shove characters and have them respond believably by swaying and stepping). It is desirable that each character's movements appear human-like, non-repetitive, and convincing, while low-level and high-level goals work together effortlessly (e.g., stepping with balanced control while steering and avoiding collisions).

Challenges: Creating crowds of pedestrian characters that possess a variety of physical properties while being interactive and engaging is challenging due to the complexity of the problem. We want to create life-like interactive characters without key-frame data and without any computationally expensive online or offline pre-processing. The crucial undertakings in brief address the task of creating autonomous agent models that are flexible, robust and computationally efficient enough to be reproduced in large numbers (i.e., crowds). The task focuses around developing and adapting model simplifications and low-dimensional assumptions to produce acceptable biped avatars that can navigate and move in realistic ways.

Our Approach: Our approach focuses on using a simplified physics-based model to create fundamental biped character motions (e.g., balancing, stepping, locomotion) that can be used to create interactive pedestrians in time critical systems, such as games. While naive techniques' approximate crowds of characters as orientated particles with bounding spheres for collision detection [ZCC*10b, Bad08], this approach can lack physical qualities, such as stepping dynamics and identifying balancing characteristics. Whereby, vital translation forces from foot placement and upper-body postural movements can *significantly* affect a character's dynamics that we attempt to embody in our approach.

Key Components and Results: We use a biomechanically inspired low-dimensional physics-based model to generate upright balancing biped stepping motions that is robust and computationally fast enough to create large numbers of autonomous pedestrian characters. We demonstrate multi-agent simulations with avatars walking around their virtual environment while the user arbitrary interacts with specific character's (and groups) by controlling their goals or disturbing them with pushes. The avatars remain balanced and upright and navigate their surrounding environment using exact foot placement sequences.

Contribution: The key contributions of this paper are a computationally straightforward and practical technique for creating controllable physics-based pedestrians that can be applied to simulate crowd situations. The pedestrians embody low-level motion characteristics, such as stepping dynamics from body-mass and ground contact forces. Furthermore, our characters' animated motions possess life-like qualities and can be customized and tailored to a variety of situations (e.g., short, fat, slow) while being non-repetitive and engaging. Motions, such as standing and walking, are generated based on physical aspects of the character and its virtual world, for example, internal and external forces, foot placement information, inertia, and strength.

2. Related Work

The subject of simulating realistic pedestrians in crowd situations is an interesting subject which has been studied across numerous disciplines (e.g., movie industry, computer games, safety and evacuation). Whereby, we briefly review some of the most recent and relevant research in the field that has contributed to making characters and crowds more *interactive and responsive*.

A common high level approach of simulating large crowds of characters is to approximate each character as an orientated particle with a collision radius. Typically, using force and velocity vectors for navigation and judgment decisions. This approach has the advantage of being computationally fast (i.e., it can simulate tens of thousands of agents), straightforward to implement, and produces reasonable life-like results. These methods can be combined with basic behavioral models [Rey99, GVK06] to perform simple functions (e.g., seek, flee, pursue, and collision avoidance) and is a popular avenue of research [PAB07, Bou08, KSA*09, LD04, vdBLM08]. For a detailed and comprehensive overview of these different crowd simulation techniques see Badler [Bad08].

Particle-based agent techniques can generate paths, which can be used to create sequences of footsteps. These footsteps have successfully been used, via forward, inverse kinematics, physics-based methods and motion capture data to generate life-like animations for crowds of characters [CBYvdP08, vBPE10, vdP97, CH99].

Extending the low-level locomotion of crowd agents to encapsulate more accurate human-like motions has been explored. Where Singh et al. [SKRF11] used an uncomplicated footstep steering mechanism based on the inverted pendulum (IP) to simulate hundreds of individual characters that possessed controllable stepping motions. Additionally, Ratner and Brogan [RB05] demonstrated balanced dynamic crowds for emergency situation (e.g., evacuating a room during an earthquake) by means of a basic balancing mechanism for identifying characters falling over during evacuation situations.

Physics-based controller models are a common method for generating automatically responsive motions (e.g., self-balancing, get-up, locomotive movements). However, they have primarily focused on solitary or small numbers of characters in static environments. For example, different controller models have been developed for specific body regions, such as upper-body movements by Zordan and

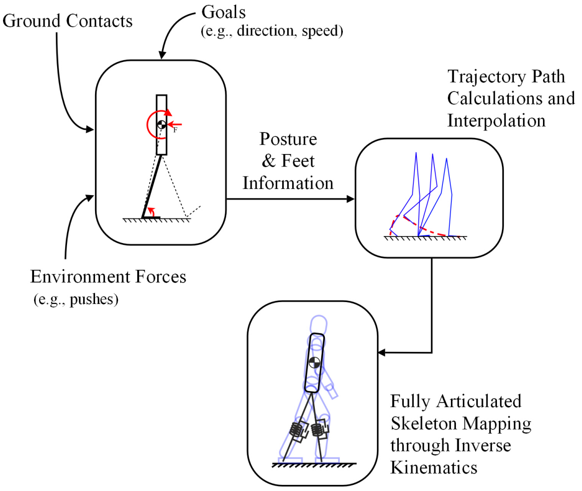

Figure 3: *Overview. A high-level view of the interconnected structure of our systems key-elements that we use to create interactive agents for our simulations.*

Hodgins [ZH02] and later by Yin et al. [YCP03], standing [AdSP07], moving and controlling [AP06], cyclic motions (e.g., walking) [KDM11, SKL07, YLvdP07a]. A popular approach by researchers for creating physics-based animations is using simplified machines to generate base motions (e.g., the inverted pendulum (IP) for locomotion) [PCT*01, KKK*03, TLC*10, CBvdP10a]. We similary adopt a low-dimensional physics-based balancing biped controller based on the IP model to create our reactive character motions. We use numerous approximations to achieve real-time results that can be used to create crowds of characters in interactive environments. Our basic pedestrian model follows a similar approach to Kenwright [Ken12b] to accomplish real-time reactive motions. However, our model uses an elongated body instead of a point-mass to synthesize the upper-body's dynamic posture.

3. Our Approach

Our model extends the computationally simple, robust, and straightforward inverted pendulum (IP) model for generating supplemental upright balancing biped motions as shown in Figure 4. The IP model is a popular low-dimensional technique for generating foot placement and center-of-mass (COM) information for upright biped characters [GPvdS12a, CBvdP10b, LKL10]. Our extended IP model was replicated multiple times to produce crowds of pedestrians that are controllable and possess balanced life-like navigation motions. The avatar agents could be controlled using elementary *high level logic* (i.e., desired direction and speed) while the underlying controller ensured the movements were physically correct and life-like (i.e., balanced with constrained stepping movements).

3.1. Enhanced Inverted Pendulum Mechanism

The rudimentary inverted pendulum principle approximates the character's whole-body as a single point-mass as shown in Figure 4(a). This point-mass is supported above a *massless* rigid-leg. Initially, the point-mass possesses potential energy and zero kinetic energy. As the point-mass begins to move (i.e., fall) it gains kinetic energy and loses potential energy. We can *instantly* move the support foot to a new location to either stop or continue locomotion of the point-mass. The foot placement location during foot support transitions enables us to control velocity and steering with a *pole-vault* like walking motion similar to real-world humans.

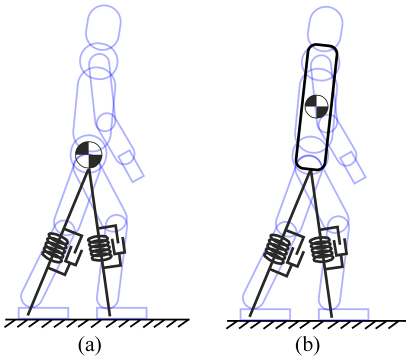

Figure 4: *Key features of an upright biped character (e.g., posture and feet locations) are used to create character animations that are highly active, dynamic, and customizable. (a) Conventional spring-loaded inverted pendulum model, and (b) our enhanced spring-loaded inverted pendulum model with an elongated rigid-body.*

3.2. Posture and Upper-Body

To make the upper-body movement take-on physical properties (e.g., mass and dimensions) and respond correctly to annoyances, such as pushes, while appearing aesthetically natural-looking, we used an elongated rigid-body instead of a traditional point-mass [YLvdP07b, MdLH10] as shown in Figure 4. Furthermore, the stick-legs were attached to the base of the elongated body instead of the centre-of-mass. Hence, we need to constantly apply a correcting torque to the rigid-body to keep it upright. This upright torque is analogues to the real-world pelvis and hip torques generated by humans. However, we use a dumb approximation system for the upper body's posture, which applies a torque to the rigid-body to keep it facing straight-up. While the rigid-body orientation torque does not integrate in any intelligent feedback from the feet contacts or balancing situation, the model could be extended by injecting feedback from the ground reaction force (GRF) into the upper-body to create more life-like postural movements during location as shown by Kenwright [KDM11].

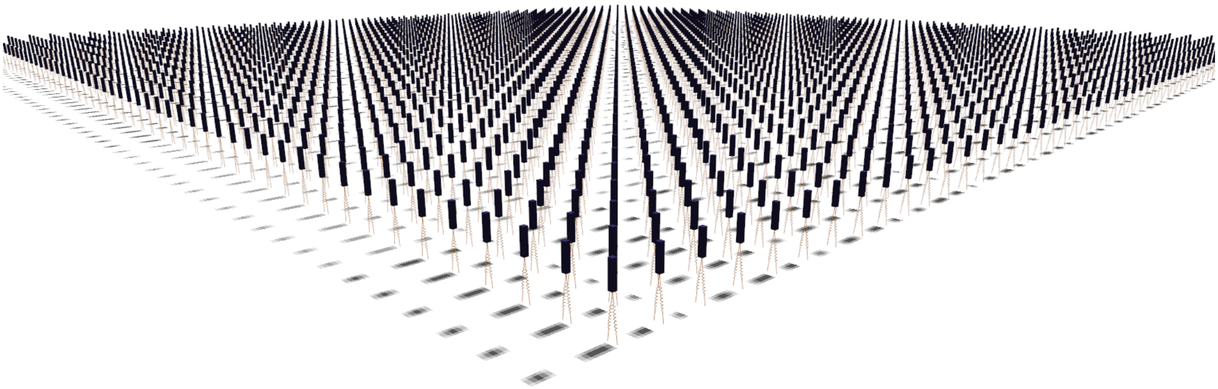

Figure 2: *Hundreds of Extended Inverted Pendulum (IP) Models. Our models uncluttered and straightforward approach of generating simple biped avatars means it is ideal for simulating large groups of interactive pedestrians. For example, the figure shows hundreds of instances of our model running in real-time.*

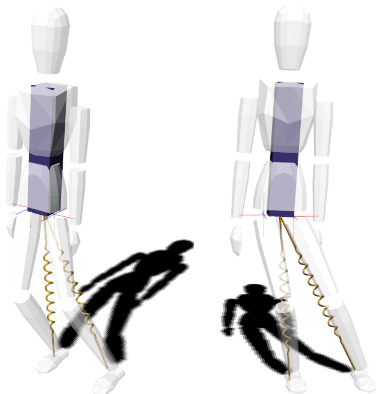

Figure 5: *The figure visually illustrates our biped model combined with our low-dimensional physics-based technique to create autonomous balancing character motions.*

3.3. Knees and Springs

A characters' legs are represented as a spring-damper mechanism, since the human muscle is mechanically analogous to a spring-damper system; consequently, spring and damping factors can be calculated to mimic how a person's limbs would respond during interactions. We use a minimalistic spring-damper model to mimic the character's leg knee bending with fixed stiffness and damping constants. Nevertheless, more elaborate *smarter* spring-damper muscle models have been developed that could be used in place of ours to mimic a more accurate muscle movement [ABP*07].

3.4. Feet and Control

While the uncomplicated IP model approximates the feet as pin-point contacts, this oversimplification means the IP model needs to constantly keep stepping to remain upright and balanced. Without compromising the IP model's speed and robustness, we add a circular foot support area that allows us to mimic ankle-torque and inject a feedback force to the upper-body centre-of-mass (see Figure 6). Furthermore, this simplified ankle-torque allows our model to possess vital properties for control, such as steering and recovering from small disturbances without needing to take a corrective step.

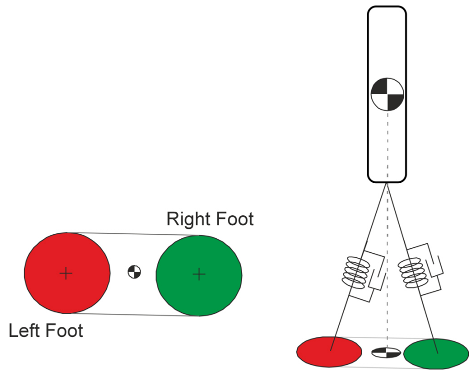

Figure 6: *The figure shows our enhanced spring loaded inverted pendulum (SLIP) model with elongated body for dynamic postural information and the simplified circular foot support area for mimicking the simulation of ankle torque, which injects additional control into the system.*

3.5. Trajectories

During foot support transitions, the foot's new position is interpolated using Bézier spline paths (i.e., swinging foot motions). While initially, we constrained the feet to follow naive elliptical trajectory during transitions, it was later found that, in reality, humans will lift their feet largely towards the start of the path. To help imitate this effect and produce stepping motions that appeared more human-like, we adjusted the Bézier spline constants to copy this as shown in Figure 7. Typically, the character's stride length was between 0.1 to 1.0m with a timing of between 0.1s to 0.7s.

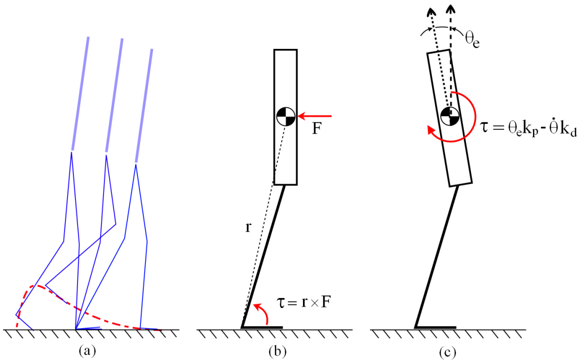

Figure 7: *(a) Feet trajectories are interpolated along Bézier spline paths, (b) a simplified foot support area mimics an approximate ankle feedback torque for controlling the upper body (i.e., for steering and balancing), while (c) the upper body has a torque applied to keep the orientation upright.*

3.6. Virtual Human Model

The 3D avatar agent used in our simulations to represent the articulated human character is shown in Figure 8. The skeleton has 30 degrees-of-freedom (DOF) limits (note an additional 6 DOF from the world root. The generic model shown in 8 has a total height of 1.77m and a weights 89.5kg with a leg length of 0.88m and an upper-body height (i.e., torso and pelvis) of 0.562m.

3.7. Full Body Inverse Kinematic (IK)

The low-dimensional physic-based model provides crucial foot placement and upper body postural information that we remap onto our highly articulated character structure using an undemanding inverse kinematic approach, since we want to synthesize large numbers of pedestrian characters for crowd situations. The IK solver ensured the physical attributes, such as joint limits, were always enforced so we did not create any implausible and painful looking poses (e.g., head and knees rotating 360 degrees).

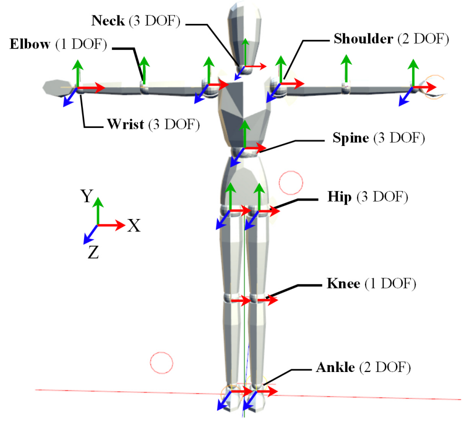

Figure 8: *Virtual Human Model*

3.8. Autonomous Agents

For large groups of characters, we implemented an uncomplicated state-logic system for the pedestrian's brain (i.e., its AI). Essentially, the characters would randomly walk about *perceiving their environment* using simple bounding sphere checks to identify their surroundings (i.e., other characters and obstacles) so that they could alter their directions. Then again, our multi-agent approach could be combined with a more advanced implementation, such as the one by Wang et al. [WDMTT12], which embodied real-time path planning and character-character interaction processing to produce a more immersive multi-agent system.

Each pedestrian had its own goals (i.e., individual instance of the state-logic system) that made decisions on how to proceed based on random unforeseen situations (e.g., arbitrary unplanned pushes) and persistent tasks (e.g., walking around and avoiding other pedestrians).

4. Experimental Results

We simulated multiple agents, which explored their virtual environment (i.e., walking around) while numerous push disturbances were applied to them (e.g., random push forces). All the generated motions were performed on a flat ground. All the simulations were carried out on an Intel Core i7-2600 CPU with 16-GB of memory running Windows-7 64-bit on a desktop PC. Typically, the average weight of the character was between 20kg and 100kg. We used a simulation time-step of 0.01s and gravitational constant of 9.81. All the simulations ran in real-time and were written as a single-threaded application. The model shown in Figure 8 was instanced multiple times with varying parameters in our virtual environment to show multiple-agents. Our implementation was written in C# using Visual Studio 2010.

Motions & Quality: We simulated different numbers of agents (i.e., from 1 to 300) doing simple predefined upright motions, for example, walking (with different speeds) and standing. In the majority of instances, our pedestrians appeared to walk around and interact (i.e., avoid obstacles) within their virtual environment happily while they were indiscriminately given small random pushes by the user of varying force and direction without complications. However, one minor artifact, on occasion, was that individual biped motions did appear stiff and robot-like, since we did not employ a whole-body rigid-body model for computational speed reasons; since the final animations were generated through IKs and interpolated trajectories.

Goals & Controllable: Each avatar had simple high-level goals, such as standing or walking (i.e., direction and speed), while the low-level goals such as balancing and stepping were automatically accomplished by the lower parts of the model.

Performance: Due to our physics-based model's simplicity (i.e., a single rigid-body and a pair of spring-damper's for each biped legs') the computational over-head was minimal. While the approach is not as fast as a naive approach, for example, using spheres for boundaries and pre-canned key-framed animations for the bipeds' movements, we were able to create large numbers of active agents in real-time to emulate small crowds. The computational overhead was divided between the graphics (rendering many instances of the avatar mesh), collision detection (between the environment and character-character proximity), inverse kinematic model (including joint constraints), rudimentary AI logic, and finally, our physics-based character model. Our approach is a usable approach with acceptable overheads for creating more detailed pedestrian motions through intelligent balancing stepping logic (see Figure 2). An approximate linear increase in computational time with the number of agents in the scene was observed and is shown in Figure 9. The computational time is based on a single core implementation using bounding boxes for the collision detection (see Figure 13).

Balance: The characters automatically remained balanced and upright during stepping, walking, and small unplanned pushes. Balancing is central for a character to appear life-like and believable and plays a crucial part in locomotive motion. For example, each character's internal rotational and translational forces such as foot placement and upper body postural movements *significantly* affect a character's dynamics. Additionally, balancing information can identify essential character specific states (e.g., about to fall, and tripping).

Terrain & Environment: While the model has the potential of adapting to complex virtual environments (e.g., uneven-terrain, buildings, stairs) we only explored simple open-plan flat terrain worlds (see Figure 12).

Disturbances & Robustness: Applying various unexpected external forces (i.e., pushes of different direction and magnitude) and varying the model's parameter (e.g., mass,

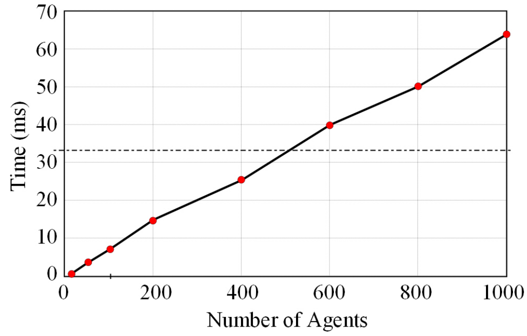

Figure 9: *Performance test for updating our algorithm for different numbers of agents (i.e., rigid-body dynamics, inverse kinematics, and collision detection). The dotted line shows the real-time threshold - limiting us to less than 500 agents for real-time environments.*

strength, and size) to demonstrate the flexibility, robustness, and practicability of our model for creating upright biped characters (see Figure 11). The random push force disturbances were applied at different locations on the upper-body and lasted between 0.1s to 0.5s with a magnitude of between 5N to 300N.

Scalability and Sensitivity: While our model is flexible and robust, it is not infallible and does require tuning and limiting of parameters to ensure the overall system remains stable (e.g., force and torque limits). Our underlying physics-based model is able to mimic an articulated character's balancing stepping motions. However, to keep our model as computationally fast as possible, so we could construct large groups of characters, we did not combine our technique with a fully articulated rigid-body skeleton. For our simulations, we used the same biped mesh model which could be instanced many times, and our model's data overhead was minimal, which allowed it to be duplicated many times without complications or significant overheads (see Figure 10).

5. Limitations and Assumptions

Assumptions: Our model makes numerous simplifications of the human model, for example, circular foot support area, mass-less legs, and fixed stiffness and damping coefficients for the knee bending. We also assume a zero friction model for the feet (i.e., no feet slipping). However, our model is computationally fast and encapsulate enough information to produce visually responsive and life-like character motions.

Limitations: We only focused on basic upright motions (i.e., standing and walking) and fundamental navigation logic (i.e., direction, speed, collision avoidance). The model would need extending to encompass additional motions, such as sitting, jumping, and climbing, to make it a more viable solution. Similarly, we neglected upper-body motions

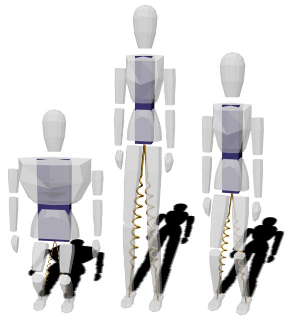

Figure 10: *Our model's features were scaled to match the type of character we aimed to synthesize (e.g., short and fat or tall and thin).*

(i.e., arm and head movements) but believe these could be integrated into the model by means of blending in key-framed data or random rhythmic animations from scripts and other sources [Per95, Ken12a]. Ideally, scripted random motions are suitable since they are flexible and can produce non-repetitive movements applicable to more natural-looking crowd environments. We did not perform inter-body collisions belonging to the same character and used simplified bounding boxes for contact information. On occasion, the motions could appear robot-like due to linear approximations for spring-damper coefficients, and not including random behavioral movements, such as arms' swaying and ankle-heal tilting. Nevertheless, the final motions possessed crucial life-like human characteristics, such as upper-body posture, foot placement dynamics and balancing.

Tuning: Since our characters' motions were generated without any key-framed data, it was necessary to hand tune various parameters, such as leg spring-damper constants and feet trajectories, to produce the most visually life-like looking movements for our simulations. Nevertheless, an offline process could be used to approximate the parameters from motion capture data. For example, Geijtenbeek et al. [GPvdS12b] used an off-line optimization search approach to calculate the elastic-damper gain coefficients for their proportional derivative joint model.

6. Conclusions

Our approach allowed us to synthesize real-time responsive biped character motions for interactive crowd simulations. The characters were able to respond to capricious push disturbances from different directions (e.g., user could arbitrarily push any pedestrian around). The final motions appeared very active and visually pleasing and did not appear to suffer from disturbing kinematic or dynamic artifacts (e.g., floating or non-balanced poses).

Due to the computational efficiency and straightforwardness of our model, it could create large interactive groups of pedestrians (i.e., crowds). While our model used a low-dimensional biped stepping approximation technique, it was able to generate engaging and life-like characters with dynamic upper-body (i.e., postural) movements.

In future, we would like to extend our model to include additional controller behaviors (e.g., falling, get-up, jumping), to enable us to emulate scenes, such as evacuation scenarios. For example, a fire or earthquake emergency where large crowds of people would rush towards the exit while pushing and shoving in an attempt to get to safety.

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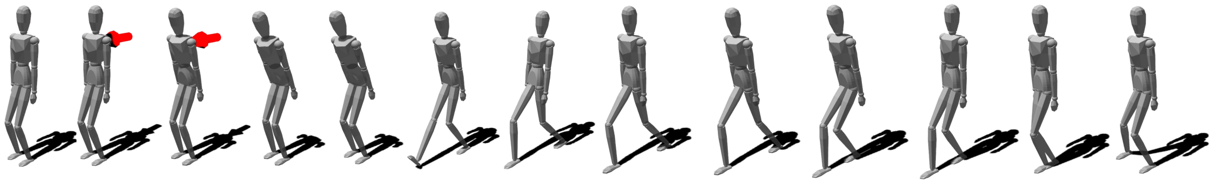

Figure 11: *Push Response. The figure shows a character having a sharp push force applied to his back which causing the posture to tilt while taking a corrective balancing step.*

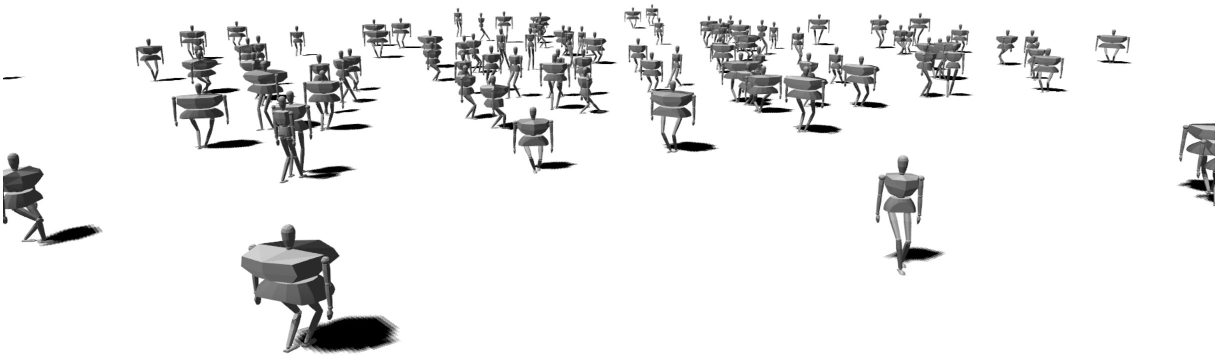

Figure 12: *Randomly Walking About. The figure shows a large assortment of characters with varying features (e.g., weight and size) roaming around.*

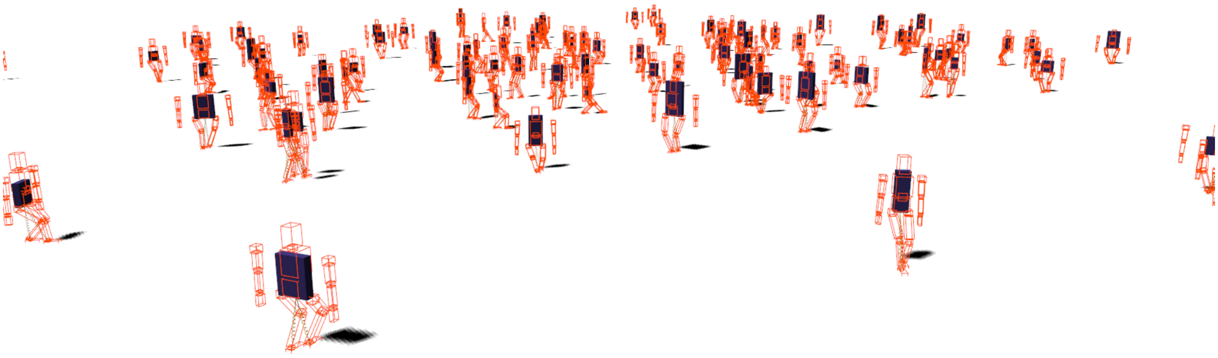

Figure 13: *Bounding Boxes. The figure shows a large assortment of characters with varying features and their bounding boxes.*

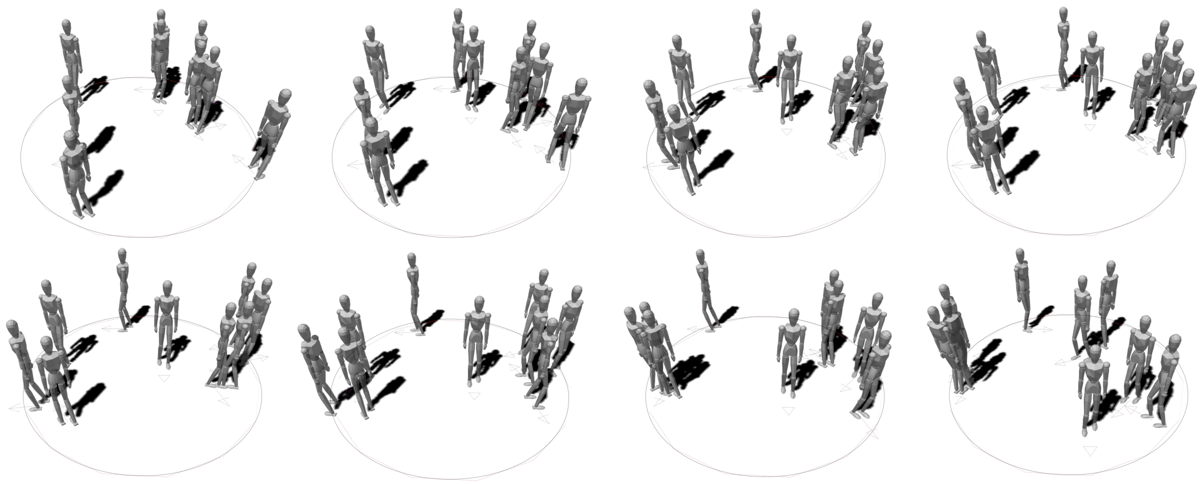

Figure 14: *Bumping. The figure shows nine biped characters repeatedly bumping into one another because they are being forced to walk in random directions, back and forth within a small circular boundary.*