NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

PHRASE: Personalized Human-Robot Interaction Simulation with Accurate Soft Body Modeling for Safe and Ergonomic Gait Assistance

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Contributions

A **first-of-its-kind** Human-in-the-Loop (HITL) simulation framework that integrates soft body dynamics to improve the realism of physical human–robot interaction (pHRI) and enable systematic evaluation of comfort and ergonomics for safer, more usable gait assistive robots:

- Personalized human soft body model synchronized with skeletal motion.
- Elastic strap model with adjustable tightness.
- Closed-loop strap controller for dynamic regulation of tightness of the strap.

BACKGROUND

- The aging population raises the demand for gait assistive robots [1] to address mobility challenges, improve rehabilitation outcomes, and easing caregiver burdens.
- Variability in gait impairments and user adaptation complicate universal robot design.
- Real-world testing is limited by ethical and safety concerns, especially for high-risk tasks such as **falls**.
- HITL simulation allows us to create a **human ability digital twin** as a guinea pig to test high risk scenarios.
- However, for scenarios such as falls, which gait assistive robots are meant to prevent, critical **soft body** dynamics are neglected in existing simulations [2].

Accurate soft body modeling is essential to capture realistic contact forces and user effects, especially during falls where straps or supports can generate large, rapidly changing loads.

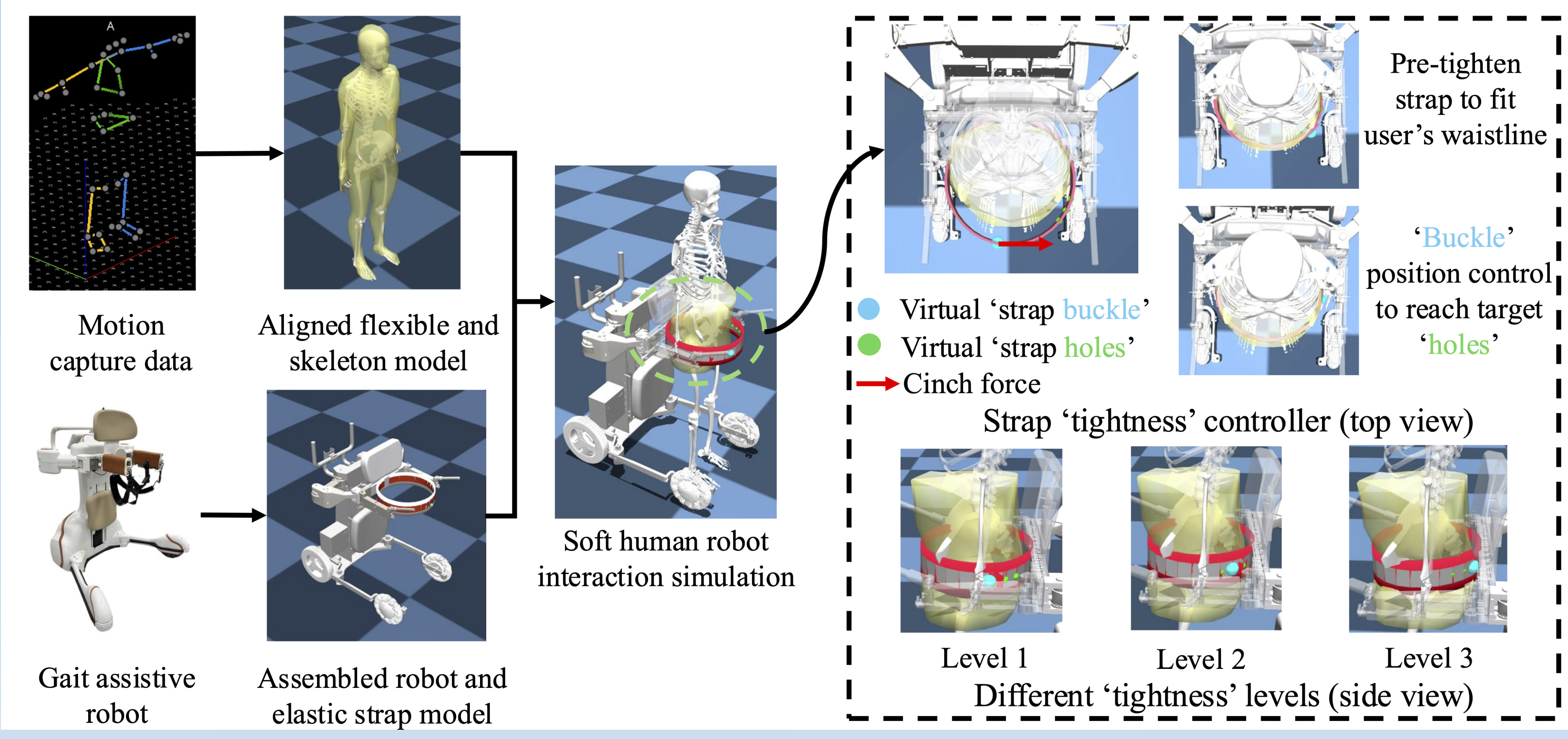

Figure 1: Overview of soft physical human–robot interaction (pHRI) simulation framework. It integrates an aligned flexible and skeleton human model and an assembled gait assistive robot and elastic strap model. The dashed box dipicts the runtime control of a virtual buckle-hole mechanism to adjust tightness levels.

METHODOLOGY

- This work extends our previous HITL simulation framework in MuJoCo by incorporating soft pHRI (Fig. 1). The framework includes three key components: (i) a **personalized soft body model** generated from motion capture data, (ii) an **elastic strap** around the pelvis with adjustable tightness and (iii) a **"tightness" controller** regulating strap tightness.
- User-specific soft body meshes are created using SKEL[4] and rigged to skeleton models following an extended method from our prior work [5]. This ensures accurate alignment of soft body deformation with skeletal motion, while allowing specific body regions of interest to be preserved for interaction studies.
- The elastic strap is modeled using the MuJoCo elasticity plugin, with dimensions matching the real-world prototype. A run-time tightening mechanism dynamically adjusts strap length to replicate different support conditions.
- A virtual "buckle" is fixed at the strap endpoint, with discrete "holes" representing different tightness levels. A feedback controller regulates the buckle position to reach the target hole, enabling systematic simulation of varying strap tightness levels consistent with real-world use.
- Two male subjects with Body Mass Index (BMI) values of 29.4 and 26.8 were simulated and compared under three tightness levels.

RESULTS

- Force distribution analysis

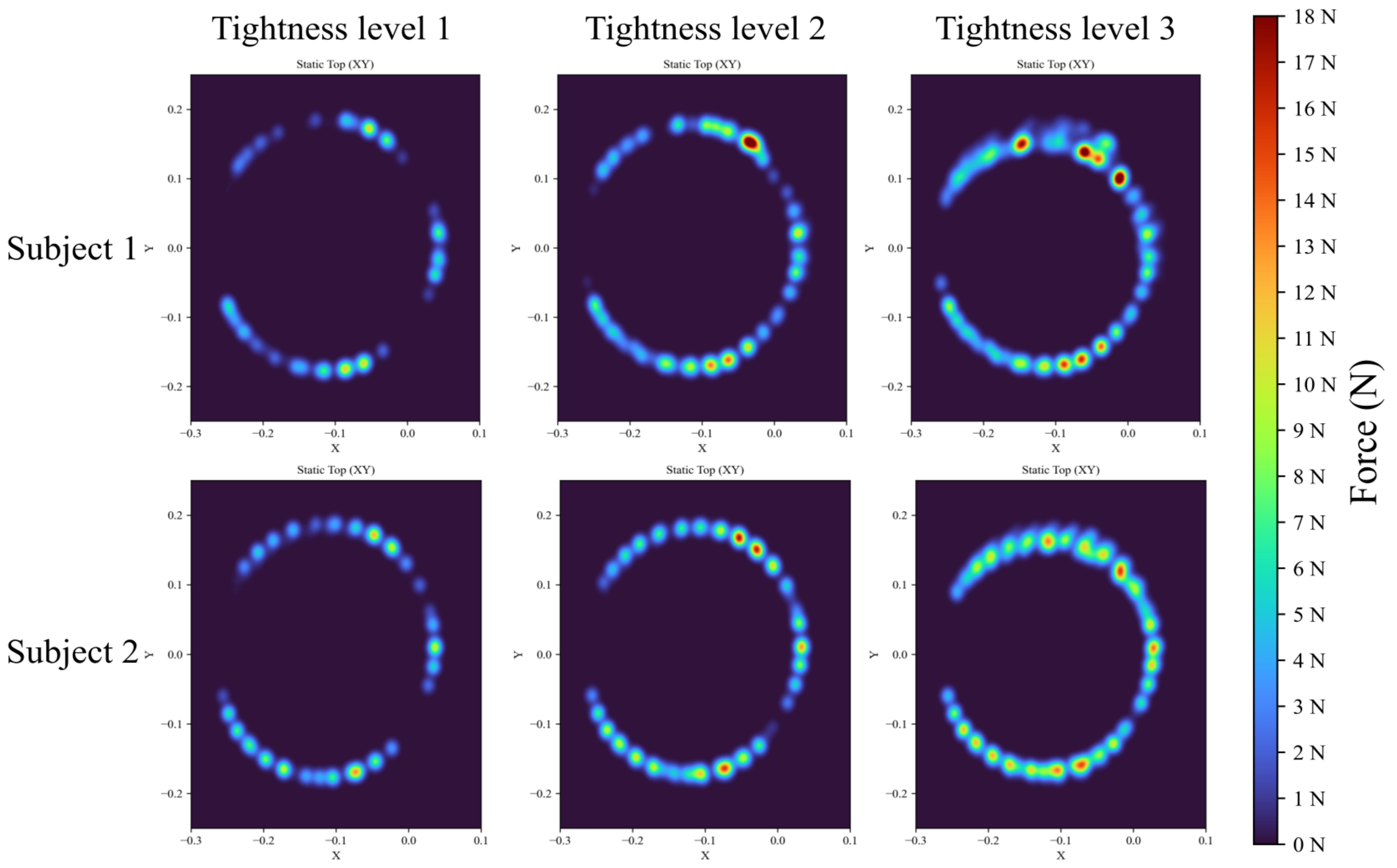

Figure 2: Force distribution around the waistline for two subjects under three strap tightness levels. Higher tightness results in increased contact forces, with peak forces indicated in red. Forces concentrate at the front and sides, while the back shows minimal loading.

Table 1: Peak force and region analysis for two subjects under three strap tightness levels

Subject	Tightness level	Peak force (N)	Peak force azimuth(°)
1	1	6.45	70.98
1	2	6.58	70.16
1	3	15.08	76.49
2	1	4.89	12.60
2	2	4.93	8.30
2	3	6.96	75.30

Video Results

DISCUSSION AND FUTURE WORK

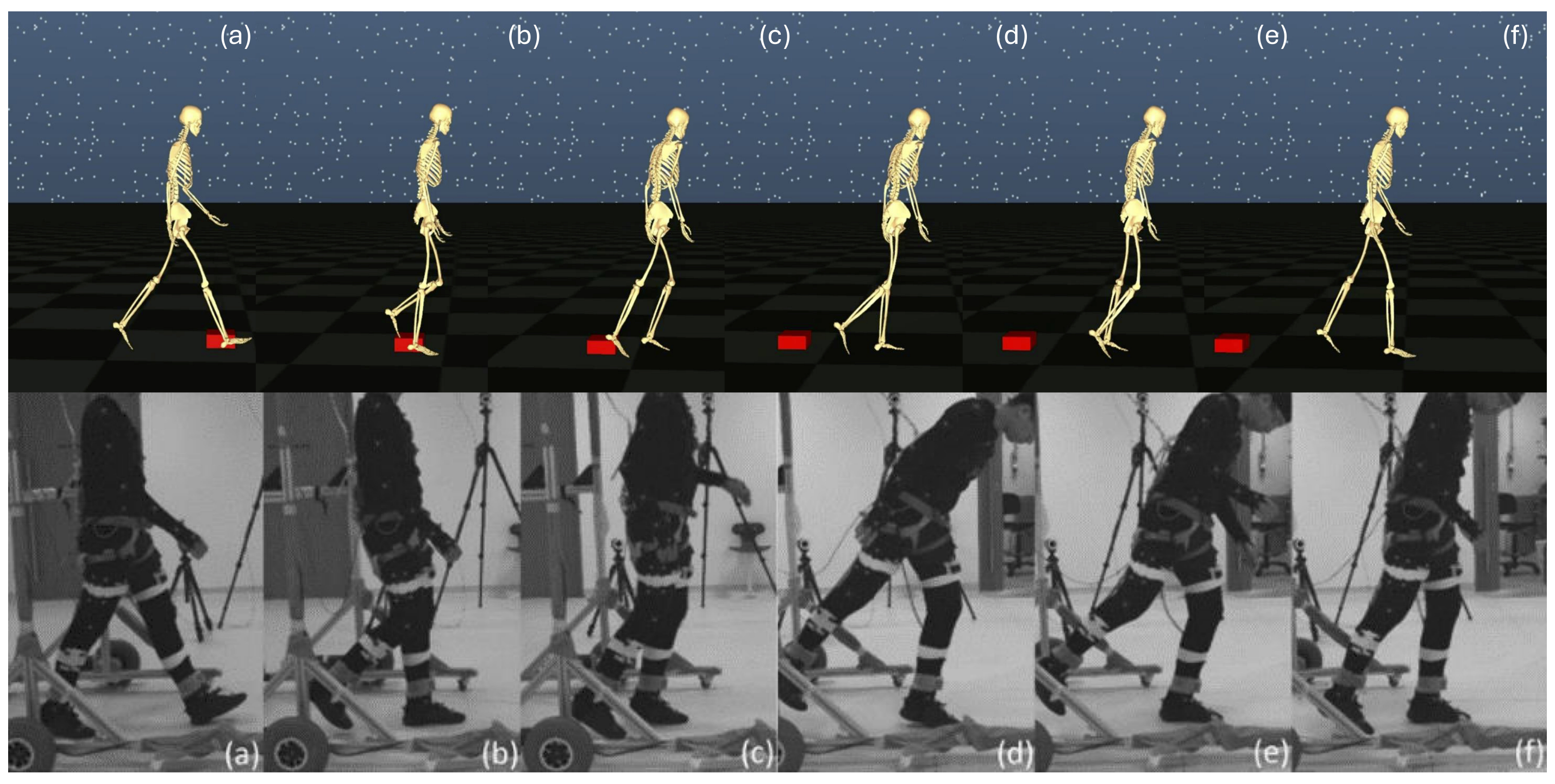

Figure 3: Comparison of simulated loss of blance during a mid-swing trip and video-recorded data with the FIMP. Trip was induced at (b).

- **Force-tightness relation**: Higher strap tightness → increased contact forces; higher-BMI subject showed greater overall loads.
- **Force spatial distribution**: Forces concentrated at the front and sides of the waistline, with minimal loading at the back—consistent with experimental observations and user feedback.
- **Ergonomics**: Simulations revealed localized peak-force regions likely linked to discomfort, providing guidance for ergonomic strap design and robot adaptation.
- **Future work**: Extend to dynamic walking and fall scenarios, enabling detailed pHRI analysis and ergonomic assessment under more realistic, safety-critical conditions.
- We have trained a digital human with reinforcement learning to develop balance recovery strategies under external perturbations. **Preliminary results** showed simulated loss-of-balance responses align with video-recorded falls using the FIMP platform (Fig. 3).

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