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

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***Index Terms*— Physical Human-Robot Interaction, Human Factors and Human-in-the-Loop, Rehabilitation Robotics**

I. INTRODUCTION

Elderly individuals often experience declining balance control, increasing fall risk. Gait assistive robots are promising solutions to provide balance support. However, variability in impairments and abilities complicates universal design, while personalization is limited by ethical and safety constraints, especially in fall scenarios.

Human-in-the-loop (HITL) simulation enables detailed study of physical human–robot interaction (pHRI) by creating a human ability digital twin as a guinea pig. However, real-world pHRI varies a lot due to strap fitting and body morphology, making it difficult to replicate in the simulation. Existing methods [1] often overlooking complex dynamics which are critical for fall scenarios. Accurate soft body modeling is therefore essential to capture realistic contact forces and user effects, especially during falls where straps and supports can generate large, rapidly changing loads.

II. METHODS

We implemented first of a kind HITL simulation framework with soft pHRI in MuJoCo (Fig. 1), integrating: **(i) Personalized soft human model** generated from motion capture data using SKEL [2] and rigged to skeletal models to preserve subject-specific body shape and motion; **(ii) Elastic strap model** implemented with MuJoCo's elasticity plugin to mimic real strap bending and twisting, dimensioned to match the physical prototype. One strap end was actuated to apply tightening force, and discrete "tightness levels" were defined along the strap; and **(iii) Strap tightness control** using a virtual buckle–hole mechanism with feedback control to reach, stablize and systematically test different strap tightness conditions.

III. RESULTS AND DISCUSSION

Demo video: `https://youtu.be/UHXQfhyTZTE`.

Two male subjects (BMI 29.4 and 26.8) were studied independently. Waistline force distributions were analyzed across three tightness levels (Fig. 2).

Contact forces increased with tightening; the higher-BMI subject experienced greater overall forces with same tightness. Forces concentrated at the front and sides, with minimal forces at the back which is consistent with experimental observations and user feedback. Simulations also reveal peak-force regions likely linked to discomfort, guiding ergonomic strap and robot design.

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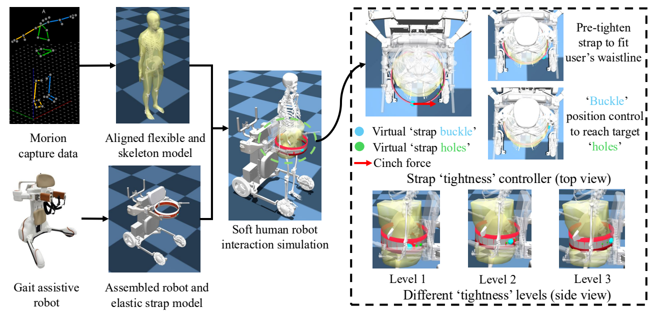

Fig. 1. Overview of the proposed soft pHRI simulation framework.

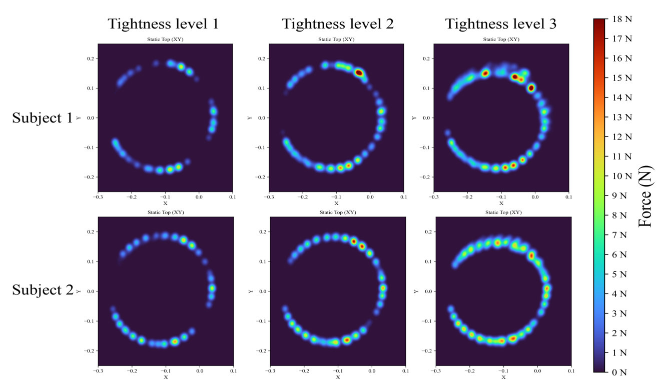

Fig. 2. Force distribution around the waistline for two subjects under three strap tightness levels.

IV. FUTURE WORK

Future work will extend to dynamic walking and fall scenarios, enabling detailed pHRI analysis and ergonomic assessment under more realistic, safety-critical conditions.

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