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Abstract（Doctor）

Title of Thesis	Virtual embodiment for multiple agents

Approx. 800 words

This thesis is inspired by the future vision of the Metaverse and Society 5.0, where cyberspace and physical space are expected to be merged seamlessly to improve our lives and also enhance capabilities of our bodies. We used Virtual Reality (VR) to investigate the Sense of Embodiment (SoE) for new types of bodies we may experience in the future Metaverse and Society 5.0 possibly through augmented virtual avatars in cyberspace or through advanced wearable robotic prostheses in the real world.

Current literature indicates that the SoE for real or virtual objects, apart from our own bodies, is typically induced through visual-tactile integration or visual-motor synchronization. However, there is a significant gap in knowledge on whether embodiment can be induced towards completely autonomous or partner-controlled limbs. To investigate this, in this thesis, we introduce a novel concept of virtual co-embodiment called the joint avatar, which is an avatar controlled by multiple individuals simultaneously. In the first experiment (chapter 4), the effects of goal and intention sharing on body ownership and agency were investigated using a joint avatar with left and right arms controlled by two different individuals in first-person view. The body ownership and agency towards the partner-controlled limb of the joint avatar were significantly higher when participants shared a common goal or could see the partner's target, compared to when the partner's target was invisible. However, participants consistently felt higher ownership and agency towards the arm they controlled. Skin conductance of participants also increased significantly when the controlled arm was threatened compared to the partner-controlled arm. The second experiment (chapter 5) examined how passive upper body movements influence body ownership and agency towards a partner-controlled arm, again using the same joint avatar. Behavioral measures included changes in body image and proprioceptive drifts. Results indicated that synchronized force feedback to the body matching the partner-controlled arm's movements significantly increased body ownership and agency. One behavioral test showed significant proprioceptive drift towards the partner-controlled arm with force feedback, indicating enhanced ownership of the partner-controlled arm in the presence of force feedback to the upper body.

The third experiment (chapter 6) explored how the speed of autonomous limb movements affects its embodiment and perception. A lower-arm prosthesis was pre-programmed to move in a minimum jerk trajectory to mimic human-like movements, and the study measured ownership, agency, usability, and robotic social attributes in a within-subject experiment. Moderate-speed movements (1 second motion time) were rated highest in ownership, agency, and usability, while the fastest (125 ms) and slowest (4 seconds) movements received lower ratings. Discomfort was lowest when embodiment and usability were highest, showing a negative correlation.

The fourth experiment (chapter 7) investigated the embodiment of biomechanically impossible arm movements using an unnatural avatar with reverse-bending arms. Participants performed reaching tasks with this avatar, with and without a 1-second delay between real and virtual movements. Results showed higher body ownership for synchronous conditions in both natural and unnatural avatars, with the natural avatar generally receiving higher ownership ratings. Agency was also higher for the natural avatar in synchronous conditions. No significant differences were observed in skin conductance responses across conditions.

In the fifth experiment (chapter 8), we examined empathic embarrassment towards humans and robots in virtual environments. Participants rated self-embarrassment and actor-embarrassment after observing human and robot avatars in embarrassing situations. Skin conductance was also measured. Results showed higher self-embarrassment and actor-embarrassment for the human avatar compared to the robot, especially in embarrassing conditions. Skin conductance responses were nearly significantly higher for the human avatar. A follow-up experiment assessed the plausibility of the stimuli, revealing that participants found the human avatar's situations more real than those of the robot avatar, particularly in embarrassing contexts.

This thesis experimentally proves that intention sharing (with a partner), passive upper-body movements synchronized with limb movements, and movement speed of partner-controlled limbs can affect the sense of embodiment. We also show that biomechanically impossible arm movements too can be embodied as long as temporal visuomotor synchrony is preserved.