VR-Based Evaluation of Torso-Driven, Hands-Free Control Strategies for Mobile Robot Navigation

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Introduction

Hands-free control of robots is an underexplored solution that addresses limitations of traditional control methods (e.g., handheld controllers) while advancing human-robot interaction (HRI). In this study, we present a torso-based navigation framework for a simulated mobile robot in a virtual environment, driven by torso motion signals captured from the Torso-dynamics Estimation System (TES) [1].

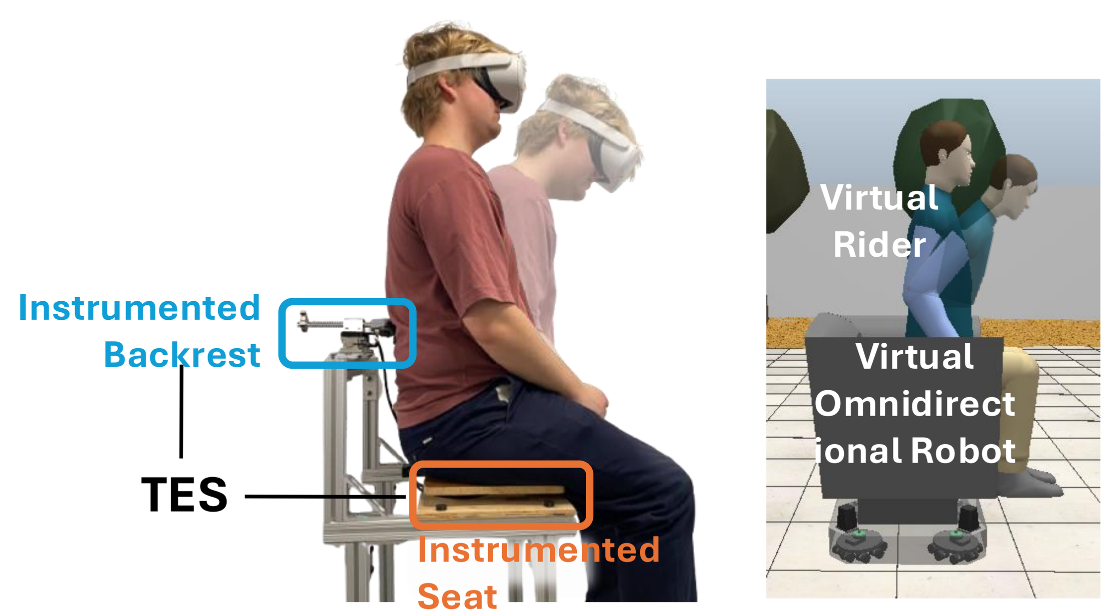


Fig. 1: HF control is used to control a virtual rider on an omni-directional robot using the signals provided by the TES. In this embodiment, the TES consists of an instrumented backrest and an instrumented seat—that measure rotation and translation of the body, respectively.

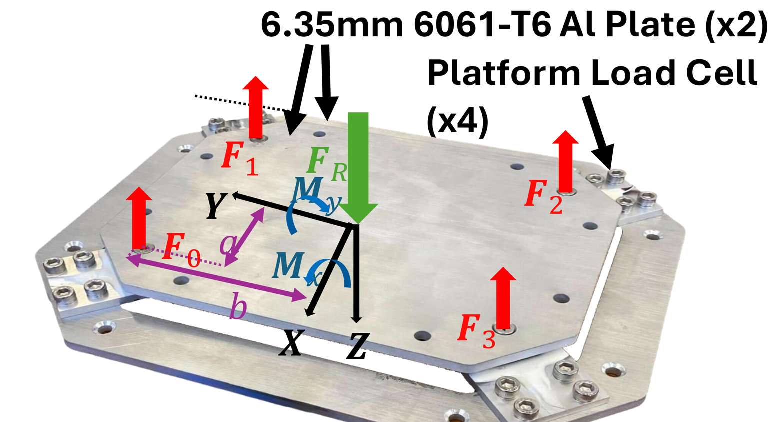
Research Question

How effectively can **torso motion signals**, captured by different sensor configurations, be used to control a virtual robot in a structured VR environment?

Custom Hardware

The TES hardware was designed and fabricated by members of the Human Dynamics and Controls Lab (see Acknowledgements). The instrumented seat measures reactive moments in the sagittal and frontal planes via four uniaxial load cells, while the instrumented backrest measures rotational displacement about the vertical axis. Together they produce the three-element reference vector used for robot command generation.

A. Compact Instrumented Seat



$$M_x = b(F_0 + F_1 - F_2 - F_3)$$
$$M_y = a(-F_0 + F_1 + F_2 - F_3)$$
$$F_R = F_0 + F_1 + F_2 + F_3$$

B. Instrumented Backrest

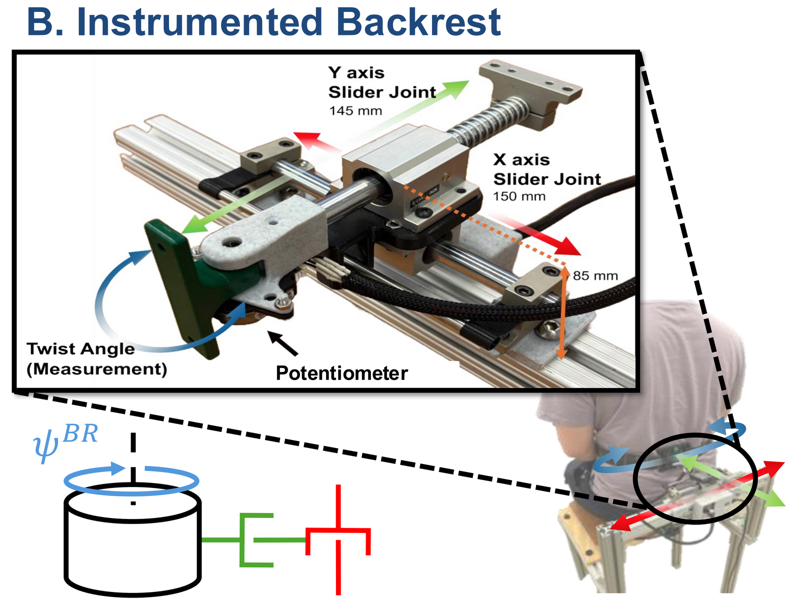


Fig. 2: **(A)** Four compact uniaxial loadcells (FRC4142_0, Phidgets, Canada) were integrated into the instrumented seat to record reactive moments in sagittal and frontal planes (M_x, M_y). **(B)** Instrumented backrest system allowing free translational movement in the X and Y directions, while measuring rotational (yaw) angle about the vertical axis using a potentiometer.

Methods – Mapping Between Virtual & Physical Environments

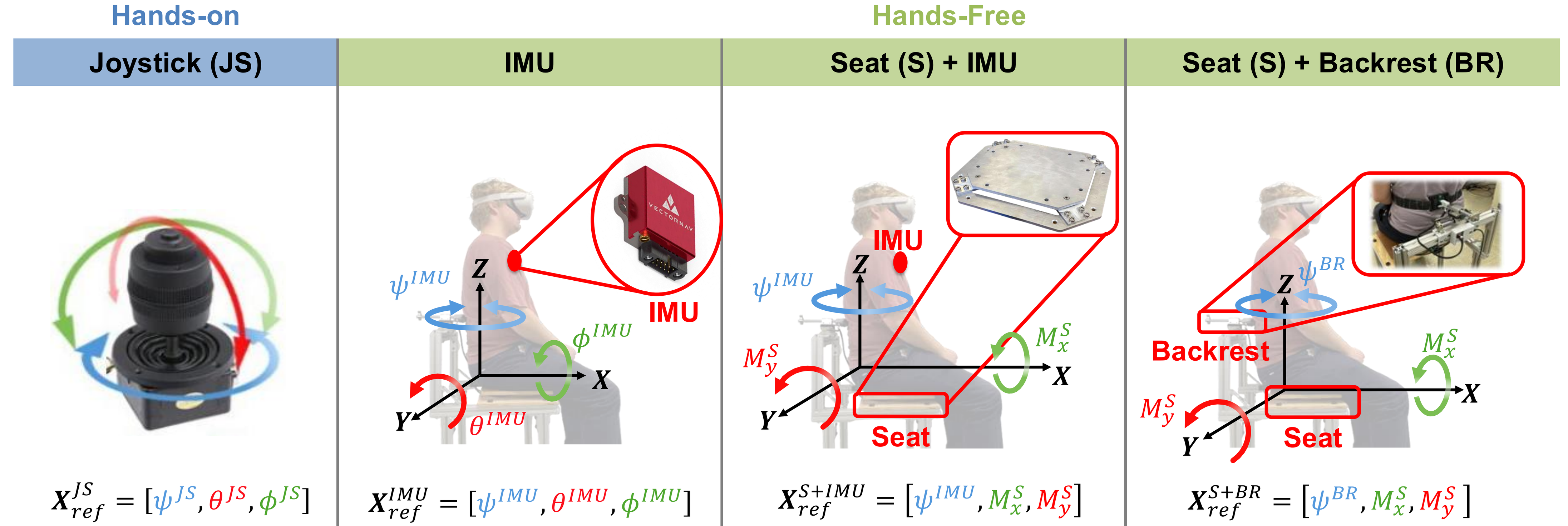


Fig. 3: Overview of the HRI system architecture: Input hardware configurations for robot control, including hands-on joystick (JS) and three hands-free embodiments using an IMU only (VN-100, VectorNav Technologies, USA), an instrumented seat (S) + IMU (yaw), and a backrest-mounted sensor (BR) (yaw) + instrumented seat.

HRI Signal Mapping

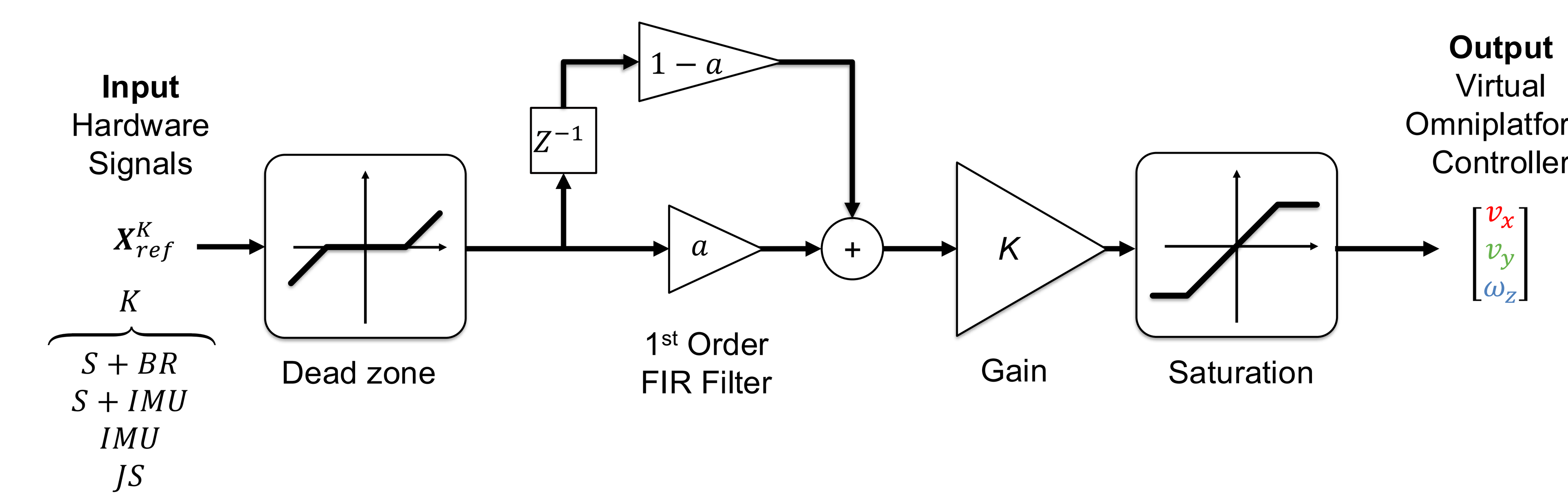


Fig. 4: Overview of the HRI system architecture: Signal processing pipeline for mapping input hardware signals to platform control commands, including dead zone filtering, first-order filtering, gain adjustment, and output saturation.

Four input configurations were implemented and compared: a hands-on joystick (JS) as a baseline, and three hands-free embodiments using an IMU only, an instrumented seat with IMU (S+IMU), and an instrumented seat with a backrest-mounted sensor (S+BR). Each produces a three-element reference vector X_{ref}^K encoding two translational and one rotational torso signal, which is then passed through a dead zone filter, first-order FIR smoother, adjustable gain K, and output saturation to yield velocity commands (v_x, v_y, ω_z) for the virtual robot.

Methods – Virtual Course Design

A VR course modeled on U.S. Building Code standards was developed to evaluate navigation performance, incorporating standard hallway widths, doorways, restroom layouts, and static and dynamic obstacles to simulate realistic built-environment navigation.

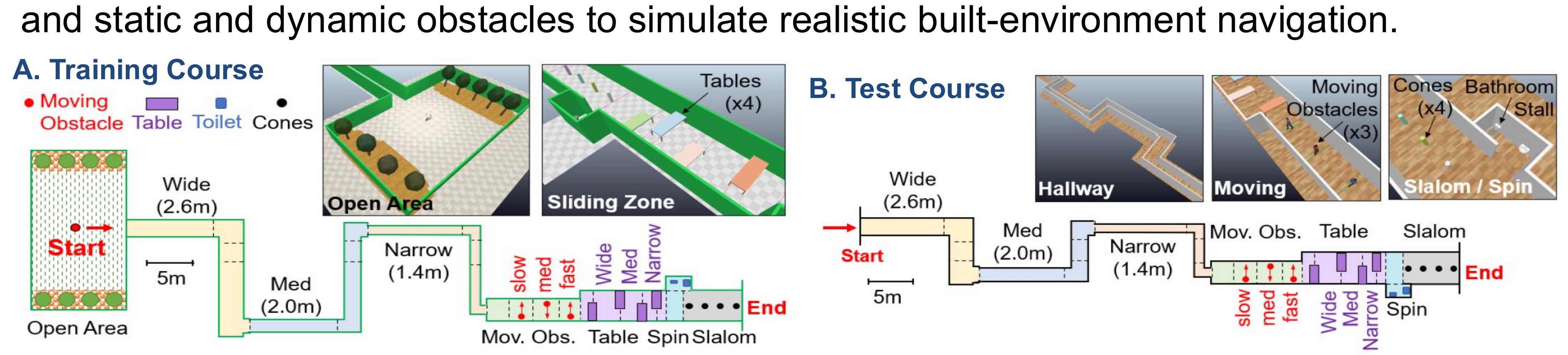


Fig. 5: Virtual training (A) and testing (B) courses

Evaluation – System Validation

The TES signal pipeline was validated by comparing VN-100 IMU orientation output against a Qualisys motion capture system, and TES seat moment signals against an AMTI force plate, across a series of controlled torso movements. Results confirmed sufficient tracking accuracy across all axes to enable reliable robot command generation.

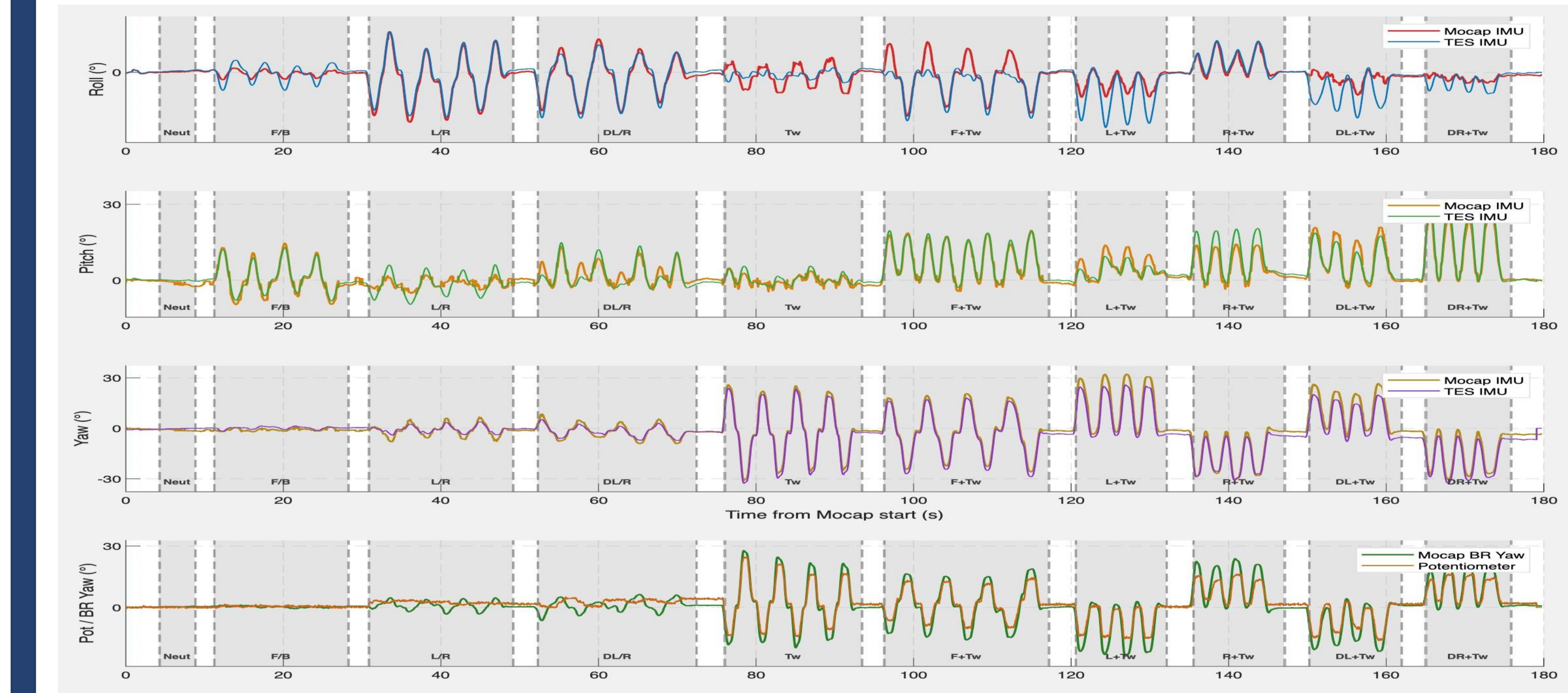


Fig. 6: Time-series comparison of TES and Qualisys motion capture signals across all sensor axes over a structured sequence of torso movements. Roll, pitch, and yaw orientations (IMU vs. mocap) are shown in the upper three panels, with backrest yaw measured by a potentiometer compared against mocap markers in the bottom panel. Shaded regions denote individual movement trials.

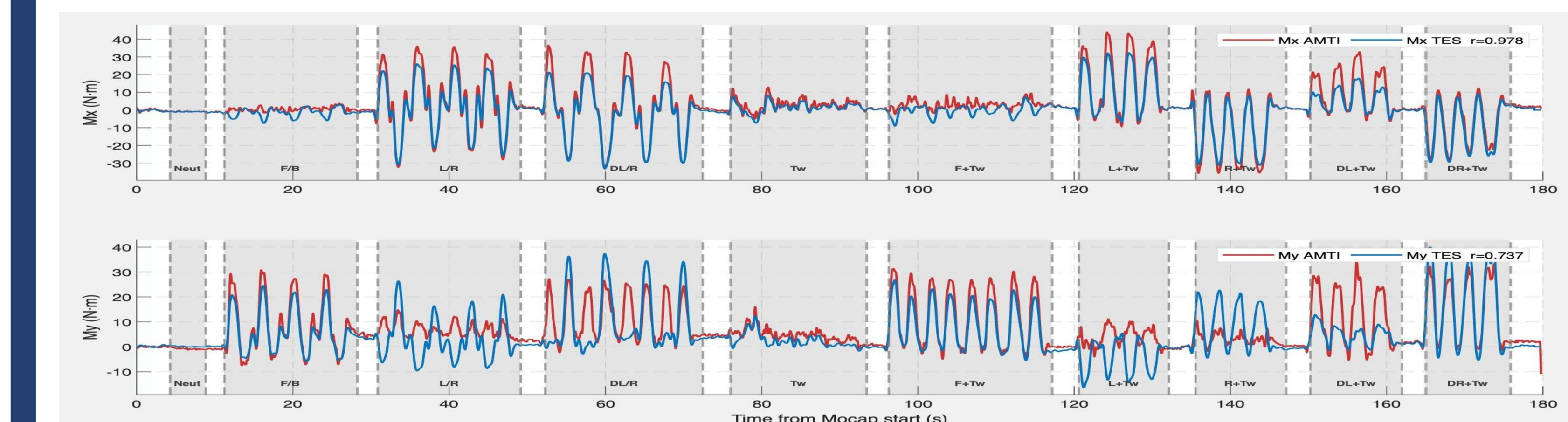


Fig. 7: Time-series comparison of seat moment signals measured by the TES and the AMTI force plate across the same trial sequence. Sagittal (Mx, top) and frontal (My, bottom) plane moments are shown.

Planned Experiment

An experiment is planned in which participants will complete the VR test course under all four input conditions: joystick (JS), IMU, S+IMU, and S+BR. Participants will complete a familiarization trial prior to each condition to minimize learning (**Fig. 5**). Primary outcome measures are task completion time and collision count, both compared against the joystick baseline to assess the effectiveness of each hands-free configuration.

References & Acknowledgements

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[1] S.Y. Song et al., U.S. Patent Pending