

Brake Operation Characteristic Design Considering Ankle Joint Passive Resistance for Full Brake-by-Wire System

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Brake-by-wire systems provide greater freedom in brake pedal design. However, current force-stroke-deceleration (F-S-G) characteristics are still mainly determined through empirical tuning, and a human-centered design methodology has not yet been established. Previous vehicle evaluations have shown that pedal force is generated even under relaxed conditions during the initial phase of braking, suggesting the involvement of factors other than voluntary muscle force.

This study focuses on ankle joint passive resistance as a biomechanical factor influencing brake pedal operation. Pedal force is modeled as the sum of muscular force and ankle joint passive resistance generated by ligaments, tendons, and passive muscle elasticity. A simplified ankle joint model is applied to estimate this passive resistance.

Based on this concept, a human-centered F-S-G design methodology is proposed. As shown in Fig. 1, a reference point is introduced in the initial braking region where pedal reaction force balances ankle joint passive resistance. This reference point is continuously connected to the conventional muscle-dominant braking region, enabling both natural initial pedal feel and controllable braking performance within a unified design framework.

Preliminary electromyography evaluations showed that pedal characteristics designed according to the proposed concept tended to reduce muscle activity around the reference point. Furthermore, muscle activity was found to correlate with ankle joint angle (Fig.2) at the non-operating position, suggesting that ankle joint angle may serve as a promising design parameter for future human-centered brake pedal systems, particularly for ultra-short-stroke pedal applications. These results indicate that incorporating ankle joint passive resistance and ankle joint kinematics into brake pedal design can improve initial pedal feel and provide a human-centered design framework for future brake-by-wire systems.

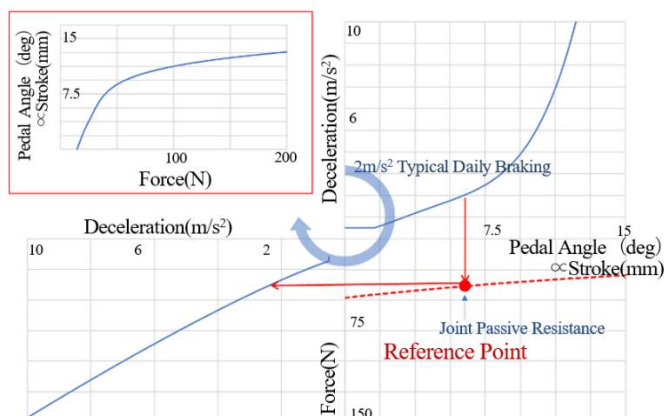


Fig. 1 Human-Centered F-S-G Design Process Method

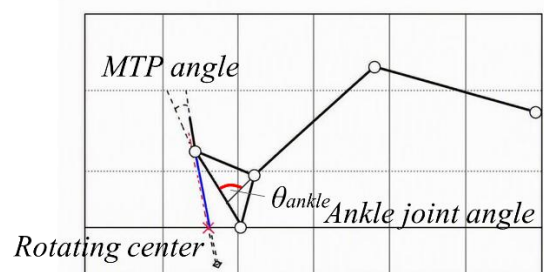


Fig. 2 Definition of Ankle Joint Angle (θ_{ankle})