Positively Missing: Reassessing Work Production in Human Gait and the Implications for Assistive Technology

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Abstract

Measuring mechanical work performed by the body is critical for understanding muscle-tendon function, joint-specific contributions and energy-saving mechanisms during gait, as well as for developing devices that assist individuals with locomotor impairments. It may therefore come as a surprise that our contemporary knowledge of work production in human gait is derived from joint- and segment-level estimates that fail to capture much of the positive work performed by the body (i.e., total work on and about the body's center-of-mass, COM). For instance, 33% of Push-off (blue bar, Fig. 1A), the total positive work done by the trailing limb during step-to-step transitions, is unexplained when we sum standard estimates of rotational joint work and deformable foot segment work (3DOF+Foot, green bar). Furthermore, much of the positive Push-off work, which is largely due to elastic recoil of the Achilles tendon and considered an energy-saving mechanism, seems to be immediately dissipated by the foot. By integrating various empirical power analyses we discovered that the missing positive work could be explained by extending conventional 3 degree-of-freedom (DOF) inverse dynamics to full 6DOF analysis (red bars, Fig. 1B). 6DOF estimates revealed 55% more hip joint Push-off work than the commonly-used 3DOF estimates, which tended to underestimate the work done at all joints. Using neuromechanical modeling we also found that the foot, rather than absorbing Push-off, may undergo its own cycle of elastic energy storage and return; a phenomenon perhaps hidden by conventional limitations in measuring biarticular muscle function. Together these findings improve our biomechanical understanding of how gait is powered, and contribute to an extended theoretical framework based on dynamic walking principles. Human-like elastic ankle Push-off (i.e., from Achilles recoil) can partially redirect the body's COM velocity between steps (from v_- to v_+, Fig. 1C), but walking still requires additional active work to offset collisional energy losses. 6DOF empirical analysis suggests compensatory muscle work is performed about the hip and knee, which could be augmented by assistive technology (e.g., Vanderbilt exoskeleton depicted). However, the active work required to walk could theoretically be reduced even further if ankle elasticity were optimally tuned to reduce collisions (Fig. 1D).