FOOT FORCE PATH LINEARITY IN THE FRONTAL-PLANE DURING PUSHES ON STATIONARY AND MOVING PEDALS

Kreg G. Gruben[1,2] and Citlali López-Ortiz[1]

Departments of Kinesiology[1], Mechanical Engineering[2], and Biomedical Engineering[2]
University of Wisconsin-Madison, Madison, Wisconsin
Email: gruben@education.wisc.edu

INTRODUCTION

The seat and pedal kinematically constrain lower limb motion during cycling such that the force of the foot on the pedal (foot force) can change its orientation through a wide range and still accomplish the objective of performing net work on the crank. Despite this latitude in force orientation, it has been shown that when humans push in the 'most comfortable manner' on a stationary or moving pedal, force orientation is tightly coupled to force magnitude (Gruben & López-Ortiz 2000). This coupling results in the head of the foot force vector tracing a straight line in the sagittal-plane. Thus, without a directional target, humans prefer to generate increases in sagittal-plane foot force through the addition of force vectors with invariant direction. These results prompted us to investigate frontal-plane foot force in order to evaluate the applicability of this mechanism to the control of three-dimensional foot force.

During kinematically constrained limb motion the forces exerted by the limb on its environment result from intersegmental joint moments, gravity, and limb dynamics (segmental masses and accelerations). Use of foot force to study motor control requires separating the effects of joint moments from the effects of gravity and limb accelerations. We can accomplish this separation by having subjects push against a stationary or pedal moving at a constant speed. In the stationary case the effect of acceleration is small and the effect of gravity is constant. In the dynamic pedaling case, if pedal speed is constant then every time the pedal passes through a specific position, the limb's posture and acceleration should be the same. Thus, changes in foot force reflect only changes in joint moments due to muscular forces. Using this technique, we can empirically determine the effect of neural control on foot force during both stationary and moving pedal conditions.

METHODS

Seated healthy human subjects (n = 11) pushed against a stationary pedal and pedaled a cycle ergometer at constant angular velocities of 10, 20, 40, and 60 rpm. Crank velocity was regulated with a feedback controlled motor. A pedal, instrumented to measure three axes of force, provided measurements of the frontal-plane components of the right foot force ($F_{medial-lateral}$, $F_{vertical}$). Digital encoders measured pedal and crank angles. All data was digitized at 200 Hz and stored on magnetic disk.

During stationary pushes the crank angle (θ_{crank}) was locked at 60, 30, 0, -30, -60° (θ_{crank}=0° corresponds to the middle of the down-stroke). These same angles are analyzed for the moving pedaling condition. For both stationary and moving conditions the subject attempted to match peak force magnitude to a target level using graphical visual feedback. For the moving pedal condition, the force magnitude target was only reached briefly during the pedal down-stroke. The target force level was sequentially set to 10 values (200, 250, 300, ..., 650 N) in random order. At each target force value, 3 s of data were acquired once the subject was comfortable achieving the target force (±10%). Foot force path in the frontal-plane was evaluated for linearity by propagating empirically-determined measurement error and considering pushes with < 2% curvature to be linear (see Gruben & López-Ortiz 2000). Force path orientation was determined using principal component analysis.

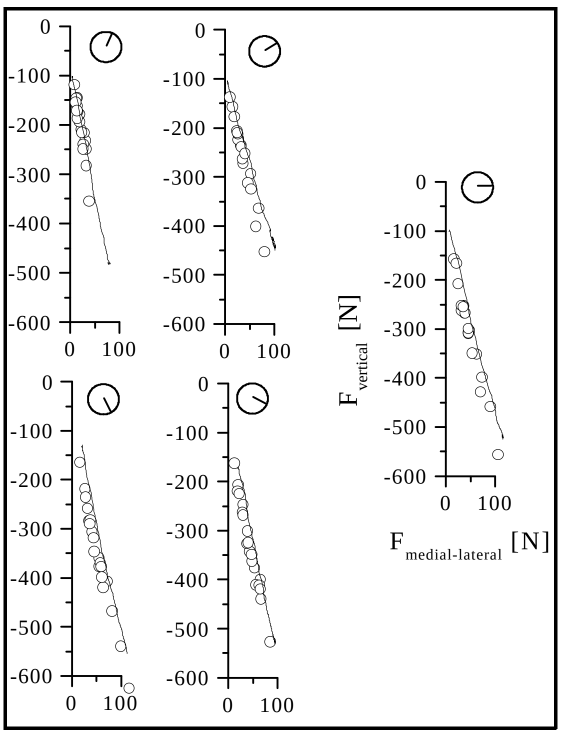

Figure 1 Sample data of frontal-plane force paths for a single subject. Each panel represents the data for a specific pedal axis location as indicated at the top of each panel. The crank rotated clockwise. $F_{medial-lateral}$ is positive in the lateral direction. Force path data for a single push against a stationary pedal is shown by the line in each panel. A force path constructed from a set of pushes against a moving pedal (40 rpm) is shown by the circles in each panel.

RESULTS and DISCUSSION

The relationship between $F_{medial-lateral}$ and $F_{vertical}$ was linear for 99% (544 of 550) of the stationary pedal pushes and 79% (171 of 216) of the moving pedal conditions (Fig. 1). The increased non-linearity for the moving pedal condition is likely due to these force paths being constructed from force generated during a series of pushes and thus includes some variability across push efforts that is not present in the stationary pedal push linearity assessment.

At a given pedal axis position, the orientation of the force paths is similar across pedal motion conditions (parallel nature of data in Fig. 1). This suggests that a similar motor control strategy may be used to generate increases in foot force despite the differences in muscle shortening velocities and limb dynamics. Offset between the force paths of Fig. 1 is due to inertial effects present in the moving but not stationary pedal conditions.

SUMMARY

Humans generate increases in three-dimensional foot force through the addition of directionally invariant force vectors. This requires precise coordination of force in several muscles and suggests that three-dimensional foot force path linearity is an invariant characteristic of motor control.

REFERENCES

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