INTRODUCTION

While it has been suggested that biarticular muscles have a specialized role in directing external reaction forces (van Ingen Schenau, 1989), it is unclear how humans learn to coordinate their muscles in force-directing tasks. Recently, we examined the ability of subjects to learn to specifically direct pedal forces during one-legged cycling, and found that subjects could significantly improve targeted pedal force direction when given real-time feedback (Hasson et al., 2006a). In the present abstract, we describe the changes in pedal and joint kinetics that took place over the learning process. After quantifying these changes, alterations in mono- and bi-articular muscle coordination were studied using electromyography, described in a companion abstract (Hasson et al., 2006b).

METHODS

Nine male subjects (age: 25±4 yrs; mass: 83±13 kg; height: 1.77±0.07 m) performed one-legged cycling on a ten-speed bicycle mounted on a computerized ergometer. Pedal kinetics were measured using a piezoelectric force pedal mounted on the left crank arm. The angular positions of the crank arm and pedal were measured with digital optical encoders. The force and angle data were sampled at a rate of 200 Hz.

Subjects were instructed to apply their pedal forces such that the resultant force was always perpendicular to the crank arm (target force direction), and to maintain a constant pedaling speed. During pedaling, real-time visual feedback (Fig. 1A) concerning the applied and target force directions and crank angular velocity (vertical bar) was displayed on a computer monitor. The crank cycle was divided into 16 sectors of equal arc length. For each sector the average error between the target and applied force directions was calculated and displayed as a vector, colored to indicate the error magnitude. After each trial, the results were displayed in summary form as the average root-mean-squared error (RMSE) in each of the four crank cycle quadrants (Fig. 1B).

Subjects performed an initial baseline trial without feedback, followed by 16 trials with real-time feedback. Each trial consisted of a 15 s two-legged pedaling warm up, followed by pedaling with only the left leg for 30 s, during which data were collected.

Kinematic and kinetic data were digitally filtered (3 Hz low-pass zero-lag fourth-order Butterworth filter), and expressed as functions of crank angle (1° resolution) using cubic spline interpolation. Pedal forces were transformed to the global coordinate system. The RMSE between the applied and target force directions was calculated for each crank cycle and trial. The bicycle and rider were modeled as a five-bar linkage (Fig. 2) with two mechanical degrees-of-freedom (Hull and Jorge, 1985). Segment lengths were measured; segment masses and inertial properties were estimated using regression equations from the literature.
Segment linear and angular accelerations were calculated numerically. Joint reaction forces and moments were computed using a standard inverse dynamics approach.

Fig. 2. Schematic of bicycle-rider system. Positive joint moments are shown.

RESULTS AND DISCUSSION

As reported in Hasson et al. (2006a), subjects showed a significant improvement in their ability to direct applied forces over the entire crank cycle (decreased RMSE from 59.7±10.9º to 21.2±5.5º [pre-post, p < 0.001]), with the greatest improvement in RMSE in the second half of the crank cycle. The signed mean force-direction error across subjects is shown in Fig. 3A, where a positive mean error reflects an applied force directed radially outward with respect to the target force direction.

With learning, the net ankle, knee, and hip extensor joint moments decreased, while the flexor moments increased (Fig. 3B). Small changes in timing were observed for the ankle and hip moments, but subjects showed a much earlier transition from a knee extensor to flexor moment with learning. These moment changes caused the shapes of the vertical and anterior-posterior (AP) applied pedal forces (Fig. 3A) to become more like the “ideal” patterns of the target force direction.

In the baseline trial, the large extension moments in the first half of the crank cycle produced a large downward pedal force and crank torque. This caused an acceleration of the crank arm, which may have made it difficult for subjects to direct the force accurately at the bottom of the crank cycle and in the second half. After training, subjects demonstrated a reduced crank torque in the range of ~0-180º. This in turn caused a more uniform crank torque and therefore a more constant crank angular velocity. Without the crank acceleration in the first half of the crank cycle, subjects were better able to direct the pedal forces correctly in the range of ~160-340º.

Fig. 3. A: Mean force-direction error, applied pedal forces, and crank torque as a function of crank angle. B: Net joint moments. See Fig. 2 for force and moment definitions. Means are across subjects.

SUMMARY

Subjects were able to improve their performance of the force-directing task significantly. With training, joint extensor moments decreased, flexor moments increased, and the knee joint moment became flexor earlier in the crank cycle. These changes lead to a much less variable crank torque over the crank cycle.

REFERENCES

Hasson CJ, et al. (2006a) CSB 14th Meeting.
Hasson CJ, et al. (2006b) ASB 30th Meeting.

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