EFFECT OF MECHANICAL PROPERTIES OF THE LOWER LIMB MUSCLES ON MUSCULAR EFFORT DURING TABLE TENNIS FOREHAND

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This study investigated the effect of the maximum isometric forces and the maximum shortening velocities of the lower limb muscles on the muscular effort during the table tennis forehand. Four male collegiate players performed table tennis forehand drives with maximum effort. We used OpenSim's static optimization algorithm to estimate the activation patterns of lower limb muscles. The cost function was the sum of squared muscle activations for all lower limb muscles, which we will refer to as the muscular effort. The simulations were repeated with the maximum isometric forces or the maximum shortening velocities of each muscle group changed by ±10% of their original values. The results suggest that increasing the maximum isometric forces of the hip extensors and adductors may be most effective to reduce the muscular effort.

KEYWORDS: muscular effort, musculoskeletal model, lower limb, table tennis

INTRODUCTION: Forehand drive is one of the most attacking shots in table tennis. Table tennis court is relatively small, which would possibly require players quicker response compared to other racket sports (Apkinar et al., 2012). Previous studies have examined joint kinematics (Iino & Kojima, 2009), joint kinetics (Iino, 2018) and EMG activity (Mansec et al., 2017) during the forehand. However, there is still little information that helps design effective strength training programs for table tennis players in light of the specific characteristics of the sport.

The maximum isometric strength and maximum shortening velocity in the muscle's force-velocity relation are important mechanical parameters that can affect sports performance. Both parameters can be improved by strength training. It is well known that neuromuscular adaptations show specificity to different training stimuli (Lamas et al, 2012; Mcbride, Triplett-Mcbride, Davie, & Newton, 2002). Furthermore, the ability to perform aerobic and anaerobic exercise varies widely among individuals (Ahmetov et al., 2012; Saltin & Gollnick, 1983), suggesting that both parameters would also show large variability among individuals. Thus, clarifying the effect of both parameters on performance in a sport may be helpful for designing strength-training programs especially suitable for individuals.

Human locomotion is thought to be performed while minimizing some form of physiological cost. Crowninshield and Brand (1981) found that electromyography activity during gait showed substantial agreement with the muscle activity pattern predicted when endurance was used as the optimization criteria. Although endurance is not the primary goal of hitting and throwing motions in sports, the ability to perform a motion with less effort and high endurance would be beneficial because hitting and throwing motions are usually repeated many times in a match. Thus, the purpose of this study was to investigate the effect of the maximum isometric forces and the maximum shortening velocities of the lower limb muscles on the muscular effort during the table tennis forehand.

METHODS: Participants were four male collegiate table tennis players. All participants were recruited from a Division I collegiate table tennis team. Mean (SD) age, height and body mass were 20.1 (1.4) years, 1.75 (0.03) m and 61.5 (4.2) kg. The task of the participants was to hit cross-court forehand drives against backspin balls with maximum effort. Balls were projected by a ball machine. The motions of the forehand drives were recorded using an eight-camera motion capture system at 250Hz. Ground reaction forces acting on both feet were recorded using two force plates at 1,000Hz. One trial per each participant was selected for analysis.

We performed simulations with the open-source OpenSim software package ver. 3.3 (Delp et al., 2007; Seth e al., 2011). We used the model published by Lai et al. (2017), who modified

the model published by Rajagopal et al. (2016) to simulate movements that involve substantial hip and knee flexion. The model was driven by 80 Hill-type muscle tendon units (MTUs) (Millard et al, 2013). The maximum isometric force of each MTU was estimated on the basis of the muscle's PCSA with an assumed specific tension of 60 N/cm^2. The maximum shortening velocities of all MTUs were 10 optimal fiber lengths per second. Actually, the lower limb and pelvis part of the model was used and two additional degrees of freedom (adduction/abduction and internal/external rotation) were added to the knee joint. First, we created participant-specific musculoskeletal models by scaling the generic musculoskeletal model to each participant's anthropometric dimensions. For each forehand trial, we generated joint angle trajectories using OpenSim's inverse kinematics algorithm. We used OpenSim's inverse dynamics algorithm to determine the joint torques of the lower limbs.
We used OpenSim's static optimization algorithm to estimate the activation patterns of muscles. The cost function was the sum of squared muscle activations for all lower limb muscles, which we will refer to as the muscular effort. We repeated the estimations with the maximum isometric forces or the maximum shortening velocities of each muscle group changed by ±10% of their original values. We divided the lower limb muscles into 10 muscle groups; the hip adductors, abductors, flexors, extensors, internal rotators and external rotators, knee flexors and extensors, and ankle plantar-flexors and dorsi-flexors.

RESULTS: Activations of the left (front) lower limb muscles were generally much lower than those of the right lower limb muscles (Figure 1). Activation levels of the right gluteus maximus, gluteus medius, adductor magnus, semitendinosus, biceps femoris and vastus medialis were high during backswing and forward swing phases of the forehand drive.

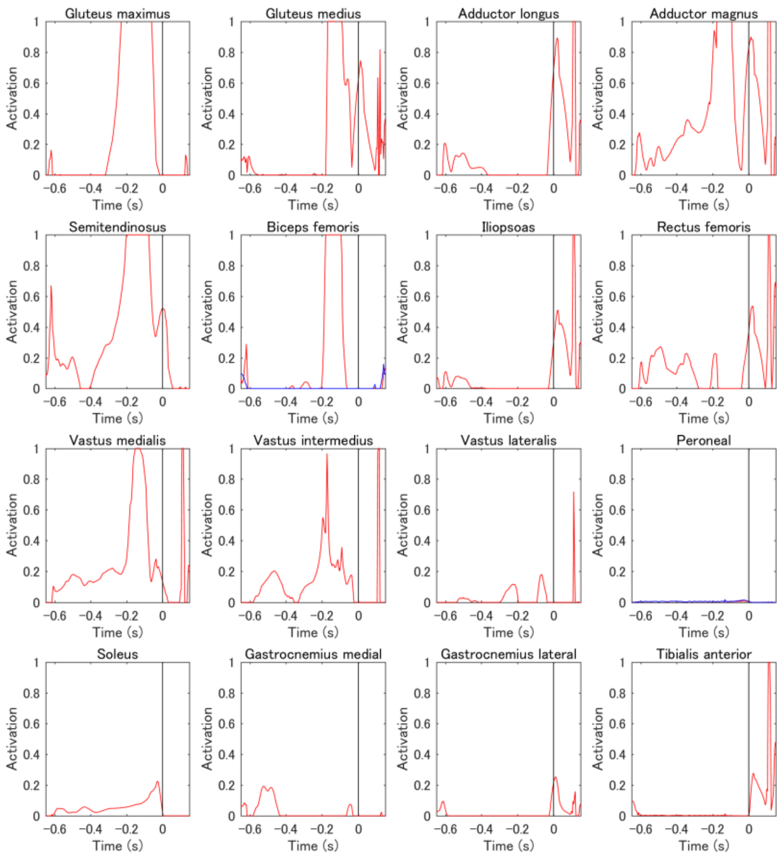

Figure 1: Activation of right lower limb muscles during a trial of table tennis forehand drive estimated by static optimization algorithm with the reference model for a representative player. 0 sec in Time corresponds to ball impact.

The muscular effort of the lower limbs was reduced most when the maximum isometric forces of the hip extensors were increased by +10% (Figure 2). The second largest reduction of muscular effort was observed for the 10% increase of the maximum isometric forces of the hip adductors, followed by those of the knee extensors, hip flexors, and knee flexors. Increases of muscular efforts were observed for 10% decrease of the maximum isometric forces of these muscle groups. The magnitude of the change in the muscular effort was larger for 10% decrease in the maximum isometric forces than for the 10% increase. The changes in the maximum isometric forces of other muscle groups had negligible effects on the muscular effort.

The muscular effort of the lower limbs was also reduced when the maximum shortening velocity of the hip extensors and adductors was increased. However, the percent reduction of the effort was about a fourth of those observed with the increase of the maximum isometric forces.

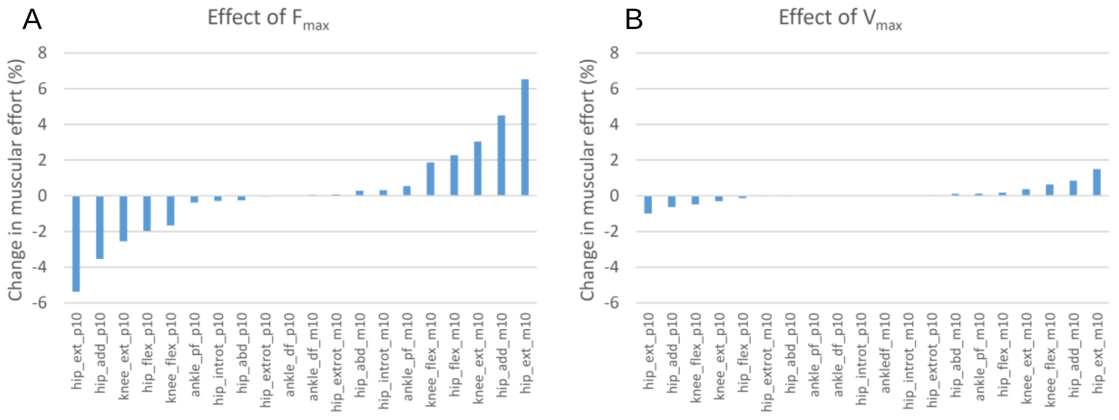

Figure 2: Percent changes in muscular effort when the maximum isometric forces (F_{max}) (A) or maximum shortening velocities (V_{max}) (B) of each muscle group of the lower limbs were changed by ±10% of those in the reference model. "p10" denotes increase by 10% and "m10" denotes decrease by 10%. Ext: extensors, flex: flexors, add: adductors, abd: abductors, introt: internal rotators, extort: external rotators, pf: plantar-flexors, df: dorsi-flexors.

DISCUSSION: This study examined the relevance of each muscle group of the lower limbs for reducing muscular effort during the table tennis forehand drive. The results suggest that increasing the maximum isometric forces of the hip extensors and adductors may be most effective to reduce the muscular effort of the lower limbs during the forehand. Although increasing the maximum shortening velocities of these muscles was also effective to reduce the muscular effort, the effect was much smaller than the effect of increasing the maximum isometric forces. This may be due to that the lower limb muscles may have exerted forces with relatively low contraction velocities and increasing their maximum shortening velocities may not have reduced the muscular effort substantially. It is also suggested that increasing both parameters of the ankle plantar-flexors and hip abductors have little effect on reducing the muscular effort. A previous study suggested the importance of hip joint torques for producing a high racket velocity in the forehand drive (Iino, 2018). The finding is consistent with the results of the present study. The results may be helpful for designing strength training programs for table tennis players.

There are some limitations in this study. First, although muscle activation patterns of the lower limb estimated by the algorithm in human walking have shown substantial agreement with observed EMG activity patterns (Crowninshield & Brand, 1981; Glitsch 1997), it is unknown if such an agreement is also observed for more forceful and dynamic sports movements. Second, we did not consider the effect of the fiber-type composition in the model of MTUs, which could affect the muscle mechanical properties. Third, the maximum isometric strengths were not scaled to each participant's specific values. Thus, players and coaches should bear in mind these limitations when interpreting the results obtained in the present study.

CONCLUSION: This study investigated the effect of the muscle maximum isometric forces and the maximum shortening velocities on the muscular effort of the lower limb during the table tennis forehand. The results suggest that increasing the maximum isometric forces of the hip extensors and adductors may be most effective to reduce the muscular effort. While increasing the maximum shortening velocities of these muscle groups was also effective, the magnitude of reduction of the muscular effort was far less than increasing the maximum isometric forces. A future study should validate the assumption of the static optimization algorithm by comparing the estimated muscle activations with independent observations such as EMG.

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