RELATIVE IMPORTANCES OF CHANGES IN MUSCLE AND TENDON INDUCED BY RESISTACE TRAINING TO CHANGES IN PERFORMANCE- A SIMULATION STUDY

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SUMMARY
The aim of the study was to determine the effects of individual adaptations in muscle and tendon induced by resistance training (i.e., muscle strength, muscle speed, and tendon stiffness) and their relative contributions to mechanical output. For this purpose, we used a forward dynamics simulation model to isolate the influences of single adaptations. A Hill-type model of the muscle-tendon complex (MTC) which casts a load vertically was constructed (Figure 1). The effects of resistance training were simulated by varying three musculo-tendon parameters that described muscle strength (+ 50%), muscle speed (+ 15%), and tendon stiffness (+ 65%), based on the data in previous studies. The results showed that, among three adaptations simulated in this study, muscle strength had a dominant effect and tendon stiffness had the smallest effect on performance. This suggested that increasing muscle strength with resistance training would be more effective than increasing muscle speed or tendon stiffness.

INTRODUCTION
Long-term resistance training induces several adaptations in muscle functions (e.g., strength or shortening velocity) and tendon properties (e.g., stiffness). These factors are thought to influence physical performance in sports and daily life activities. To design appropriate training protocols, it is important to understand how much each adaptation influences performance and what effects are most significant. However, it is difficult to determine how much each factor contributes to performance in an experimental setting, because resistance training causes simultaneous changes in muscle and tendon parameters. Thus, no previous studies have determined the relative impact of muscle and tendon adaptations on performance. In this study, we used a forward dynamics simulation model to isolate the effects of single adaptations by selectively altering parameters that described individual muscle and tendon functions. With this approach, we aimed to determine the effects of individual adaptations in muscle and tendon parameters induced by resistance training and their relative contributions to mechanical output.

METHODS
A Hill-type computer simulation model of the MTC was constructed (Figure 1) [1]. The model consisted of two elements, a contractile element (CE) and a series elastic element (SEE). All model development procedures and the numerical integration of ordinary differential equations were performed with MATLAB (The Math Works, Inc., Natick, MA, USA).

Default parameter values of CE were defined based on results from a previous study [2]. The maximal isometric contraction force of CE (F_{max}) was 550 N and the optimal length of CE (L_{opt}) was 0.1 m. The slack length of SEE (L_{slack}) was defined as 0.2 m to ensure that the length ratio between CE and SEE (i.e., fiber and tendon) were approximately consistent with that of the mm. vasti [3,4]. Mathematical representations of the MTC model, including force-length and force-velocity relationships of CE, and the SEE quadratic elastic property were based on the model from a previous study [2].
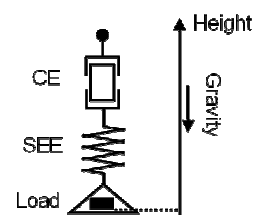

Figure 1: The Hill-type muscle tendon complex model used in this study.

The effects of resistance training were simulated by varying three musculo-tendon parameters: (a) muscle strength, represented by F_{max} [N], (b) muscle speed, represented by the maximum shortening velocity (V_{max} [m/s]), and (c) tendon stiffness, represented by SEE stiffness (S_{tendon} [N/mm]). The magnitudes for modifying each parameter (Δ) were based on experimental data reported in previous studies. We defined the maximum effects of resistance training as a 50% increase in maximal muscle force (ΔF_{max}) [5], a 15% increase in muscle shortening velocity (ΔV_{max}) [6], and a 65% increase in tendon stiffness (ΔS_{tendon}) [7].

In the model, a load was represented by a mass, which was cast vertically in the gravitational field with a pre-tension. The mass was varied to impose a force between 0.05 F_{max} (5% load) and 0.40 F_{max} (40% load) in the gravitational field. After the mass was released, the gain in height achieved by the mass (H_{gain}) was evaluated from the resting MTC length ($L_{opt} + L_{slack} = 0.3$m). Because the initial length of the MTC would influence the H_{gain}, the start position of simulation was varied in 0.005m increments, within $\pm$ 0.04m from the resting MTC length. Among the trials at different initial positions, the largest H_{gain} value achieved with a given mass was defined as the model performance. The effect of resistance training was evaluated by comparing the difference in H_{gain} between the default (unmodified) model and the trained (modified) model (ΔH_{gain}).

RESULTS AND DISCUSSION
The results of H_{gain} in individual parameters and the combined effects were summarized (Table 1). Regardless of the load size, increasing the F_{max} parameter of the model resulted in the largest increase in performance (Figure 2: ΔH_{gain} was + 0.0252m with 5% load, + 0.0072m with 20% load, and + 0.0078m with 40% load), compared to

increasing V_{max} (Figure 2: ΔH_{gain} was + 0.0120m with 5% load, + 0.0048m with 20% load, and + 0.0023m with 40% load) or S_{tendon} (Figure 2: ΔH_{gain} was - 0.0097m with 5% load, + 0.0001m with 20% load, and + 0.0016m with 40% load). These results suggested that the largest enhancement in muscular performance could be achieved by focusing resistance training on increasing the physiological cross-sectional area of the muscle (i.e., F_{max}). This finding was consistent with the previous one that the influence of F_{max} was larger than that of V_{max} on jumping performance [8]. The current results showed that, even when an adaptation in tendon tissue is taken into consideration, increasing muscle strength remained the dominant factor that contributed to the enhancement of performance.

Increasing S_{tendon} parameters decreased the ΔH_{gain} (- 0.0097m) with a light load (5% F_{max}). This indicated that increasing the tendon stiffness in resistance training might negatively affect performance for some types of movements. Moreover, although increasing the S_{tendon} parameters increased the ΔH_{gain} with medium and heavy loads (20% and 40% F_{max}), the absolute augmentation values were relatively small (ΔH_{gain} was +0.0001m and 0.0016m, respectively). Thus, the small influence of S_{tendon} on H_{gain} suggested that tendon tissue adaptations would be less important than the other adaptations for improving performance.
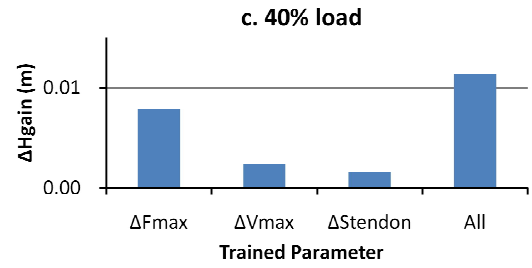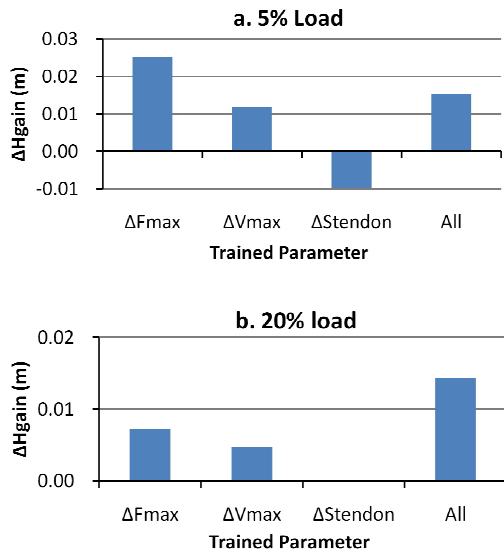

c. 40% load

Figure 2: Changes in performance produced by resistance training-induced adaptations in individual parameters and the combined effects (All).

CONCLUSIONS

In this study, a Hill-type MTC model was used for systematic simulations of the adaptations induced by resistance training and their effects on muscular mechanical output. The results showed that, among three adaptations simulated in this study, muscle strength had a dominant effect and tendon stiffness had the smallest effect on performance. This suggested that increasing muscle strength with resistance training would be more effective than increasing muscle speed or tendon stiffness.

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a. 5% Load

b. 20% load

Table 1: The results of gain in height achieved by the mass (H_{gain}) in individual parameters and the combined effects (all modified) in each load size. The values were evaluated from the resting MTC length ($L_{opt} + L_{slack} = 0.3m$).

Load Size	Trained Parameter				
	Unmodified	**ΔF_{max}**	**ΔV_{max}**	**ΔS_{tendon}**	**All Modified**
5% Load	0.0861m	0.1113m	0.0981m	0.0764m	0.1013m
20% Load	0.0522m	0.0594m	0.0570m	0.0523m	0.0666 m
40% Load	0.0402m	0.0481m	0.0426m	0.0418m	0.0516m