Association between passive stiffness of hamstring and eccentric knee flexion angle-torque relationship

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Abstract Larger hip flexion range of motion with knee extension (hip flexion ROM) and passive stiffness of the hamstring is associated with greater production of isometric and concentric knee flexion torque at longer muscle lengths. Nevertheless, associations among hip flexion ROM, passive stiffness of hamstring, and eccentric knee flexion torque at a longer muscle length remain unclear. Therefore, we aimed to investigate the association among hip flexion ROM, passive stiffness of hamstring and eccentric knee flexion angle-torque relationship. Seventeen healthy male college students participated in this study, and all measurements were performed on both legs (34 legs). No participants had any previous hamstring strain injury. Hip flexion ROM, passive stiffness of hamstring, peak torque and peak torque angle during isokinetic eccentric knee flexion were measured. The correlation among the variables of interest were assessed. Passive stiffness of hamstring and eccentric peak knee flexion torque negatively correlated with the peak torque angle ($r = -0.39$). On the other hand, peak torque angle was not correlated with hip flexion ROM ($r = 0.08$). The present study revealed that higher passive stiffness of hamstring was associated with greater production of eccentric knee flexion torque at longer muscle lengths.

Keywords : hamstring, eccentric contraction, peak torque angle, range of motion, passive stiffness

Introduction

Hamstring strain injury is a prevalent non-contact injury¹⁻³. The hamstring is susceptible to acute muscle strain resulting from excessive force during sprinting^{1,2}, because the hamstring requires substantial eccentric contraction power at longer muscle lengths to absorb hip flexion and knee extension moment to decelerate lower limb momentum during the late swing phase of sprinting^{4,5}. Therefore, greater eccentric hamstring strength^{6,7} and production of larger muscle force at longer muscle lengths might decrease the risk of hamstring strain injury^{8,9}.

Muscle force at longer muscle lengths is affected by the range of motion (ROM), which is an indicator of flexibility, and passive muscle stiffness, and, in turn, an indicator of viscoelasticity. Previous studies reported that subjects with larger hip flexion range of motion with knee extension (hip flexion ROM) could perform greater isometric and concentric knee flexion torque at longer muscle lengths compared to subjects with smaller hip flexion ROM^{10,11}. Moltubakk et al. (2016) demonstrated lower passive stiffness of hamstring related to the production of greater concentric knee flexion torque at longer muscle

lengths¹². This relationship seems to be influenced by the actin-myosin overlap¹³. Optimal actin-myosin overlap is determined by the combined influences of the compliance of series elastic elements and muscle length. A subject with larger ROM and lower passive stiffness may present more compliance and/or longer hamstring; therefore, enabling the subject to perform greater muscle force during contraction at longer muscle lengths. Nevertheless, the relationship among hip flexion ROM, passive stiffness of hamstring and eccentric knee flexion torque at longer muscle lengths remains unclear. Owing to the correlation among the eccentric, isometric, and concentric muscle forces^{14,15}, this relationship in eccentric knee flexion may be similar to the results of previous studies. However, hamstring strain injury is considered to occur during eccentric contraction at longer muscle lengths^{16,17}. Accordingly, determining the relationship among hip flexion ROM, passive stiffness of the hamstring, and eccentric knee flexion torque at longer muscle lengths can be more helpful in preventing hamstring strain injury.

Therefore, this study aimed at determining the association of hip flexion ROM, passive stiffness of hamstring and the eccentric knee flexion angle-torque relationship. We hypothesized that larger hip flexion ROM and lower passive stiffness of hamstring would be associated with

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the production of greater eccentric knee flexion torque at longer muscle lengths.

Materials and Methods

Participants. Seventeen healthy male college students (mean $\pm$ standard deviation: age, 24.9 ± 2.5 years; body mass, 67.8 ± 7.0 kg) voluntarily participated in this study, and all measurements were performed on both legs (34 legs). None of the participants had regularly performed lower limb resistance training in the past or experienced a hamstring strain injury.

This study was reviewed and approved by the institutional review board of the University of Tsukuba (approval number: 28-59) and was conducted in conformity with the principles of the Declaration of Helsinki. All study procedures and potential risks were explained to the participants, and the participants provided written informed consent before participation in this study.

Procedures. The experimental protocol included two visits. The first visit was at least 2 days before the experimental session, during which all participants familiarized themselves with the measurements. Furthermore, the positioning of the dynamometer (e.g., seat position, lever arm angle, and height) for each participant was determined during familiarization. The second visit was an

experimental session. Before the experimental session, participants performed a 5-min warm-up (60–70 rpm at 50 W) using a stationary bike (M3 Indoor Bike; Keiser Corp., Fresno, CA, USA). All variables of interest were measured in both legs. On the day before testing, the participants were not exposed to any high training load.

Hip flexion ROM. The SLR test was performed to measure the hip flexion ROM. The participants were in the supine position on an examination bed, and the pelvis and thigh of the non-tested leg were secured using straps. One investigator raised the participant's leg with the participant's knee being passively extended until the point which the participant felt a strong but tolerable stretch, slightly before the occurrence of pain¹⁸⁾, and another investigator measured the hip joint angle at this point by a goniometer.

Knee extension ROM, passive torque, and passive stiffness. Participants were seated on an isokinetic dynamometer (Biodex System 3; Biodex Medical Systems, Inc., Shirley, NY, USA) with both hip joints flexed 120° by the attachment for fixation, and the trunk was perpendicular to the horizontal plane by insertion of a wooden frame between the trunk and backrest (Fig. 1). The lateral epicondyle was aligned with the axis of the dynamometer. With the participants seated in this position, the knee joint was passively extended at $5^\circ/\text{s}$ from the initial position

Fig. 1 Setup of isokinetic dynamometer when measuring knee extension ROM, passive torque, and passive stiffness.

(knee flexed at 90°) to the point which the participant felt a strong but tolerable stretch, slightly before the occurrence of pain, during which the passive torque was recorded to obtain a passive torque-angle curve¹⁹.

The range from the initial position (knee flexed at 90°) to the maximum knee extended angle was defined as the knee extension ROM, and the passive torque was recorded that occurred at the maximum knee extended angle (Fig. 2)¹⁹. Passive stiffness was defined as the slope of the regression line calculated from the passive torque-angle curve above 50% of the knee extension ROM using the least squares method. Passive torque shows the passive tension produced by a series elastic element, and lower passive stiffness indicates higher extensibility (lower vis-

Fig. 2 Typical examples of passive torque-angle curve during passive knee extension.
①: knee extension ROM, ②: passive torque, ③: slope of regression line between 50% and 100% defined as passive stiffness.

coelasticity) of the muscle-tendon unit.

Peak torque and peak torque angle. Participants performed eccentric isokinetic testing using an isokinetic dynamometer (Biodex System 4; Biodex Corp.). The experimental protocol was adopted from a previous study²⁰. Participants were secured in the prone position on an isokinetic dynamometer with a neutral hip joint position (flexion angle of 0°), and the upper back region and pelvis were stabilized using Velcro straps (Fig. 3). The axis of rotation of the dynamometer lever arm was aligned with the lateral epicondyle of the femur. The ROM was set from the flexed position of 90° to 10° (0° = full knee extension). We set the angular velocity at $60^\circ/\text{s}$ because previous studies reported that eccentric knee flexor strength at $60^\circ/\text{s}$ was associated with hamstring strain injury risk^{7,21}. During testing, participants continuously resisted the knee extension movement of the dynamometer through the entire ROM. Before testing, participants performed four submaximal and two maximal contractions as a warm-up²⁰. After the warm-up, participants performed three maximal voluntary contractions for testing. Participants were verbally encouraged by the investigator to generate the maximal force for the entire ROM.

Torque values from testing were extracted and sorted according to the direction of movement and knee angle. These data were compressed using a decimation function that averaged every ten successive data points and shown in the form of an active torque-angle curve^{8,22}. The peak torque and peak torque angle were determined by this active torque-angle curve. A smaller peak torque angle indicates that the peak torque was produced at a longer muscle length.

Statistical analyses. All data were expressed as a mean $\pm$ standard deviation. The Shapiro–Wilk test was used to assess the normality of all parameters. To evaluate the relationship among the hip flexion ROM, passive stiffness

Fig. 3 Setup of isokinetic dynamometer when measuring peak torque and peak torque angle.

of hamstring and eccentric knee flexion angle-torque, the correlations among the peak torque angle and other variables of interest were assessed using Pearson's correlations for parametric data, while Spearman's rank correlations were computed for nonparametric data. Statistical significance was set at $P < 0.05$ for all comparisons. Statistical analyses were performed using SPSS software version 24 (SPSS Inc, Chicago, IL, USA).

Results

Correlation among the peak torque angle and other variables of interest. The characteristics of the participants are summarized in Table 1. Peak torque angle was significantly correlated with peak torque ($r = -0.69$, $P < 0.01$) and passive stiffness ($r = -0.39$, $P = 0.02$) (Figs. 4 and 5). A significant correlation was also revealed between peak torque and passive stiffness ($r = 0.4$, $P = 0.02$) (Fig. 6). However, peak torque angle was not correlated with hip flexion ROM ($r = 0.08$, $P = 0.65$) or knee extension ROM ($r = -0.09$, $P = 0.65$). In addition, there wasn't any significant correlation observed between peak torque and hip flexion ROM ($r = 0.11$, $P = 0.53$) or knee extension ROM ($r = 0.14$, $P = 0.45$).

Table 1. Characteristics of the participants

Peak knee flexion torque, Nm/kg	1.42 ± 0.30
Peak torque angle, °	18.3 ± 13.1
Hip flexion ROM, °	80.1 ± 11.3
Knee extension ROM, °	79.9 ± 8.1
Passive torque, Nm	54.7 ± 11.9
Passive stiffness, Nm/deg	0.83 ± 0.15

Fig. 4 Correlation between peak torque angle and peak torque.

Discussion

This cross-sectional study showed that higher passive stiffness of hamstring was correlated with smaller peak torque angle. These results suggest that higher passive stiffness of hamstring could be related to the production of greater eccentric knee flexion torque at longer muscle lengths.

Previous studies reported that larger hip flexion ROM was associated with the production of greater isometric and concentric knee flexion torque at a longer muscle length^{10,11}. By contrast, the present study demonstrated no association among hip flexion ROM, knee extension ROM and peak torque angle during eccentric hamstring contraction. Moreover, contrary to the previous study¹², our results showed that higher passive stiffness of hamstring was associated with the production of eccentric peak knee flexion torque at a longer muscle length. The reason for the discrepancy between the results of the pre-

Fig. 5 Correlation between peak torque angle and passive stiffness.

Fig. 6 Correlation between peak torque and passive stiffness.

vious study and the present study is thought to be due to the difference in contraction mode. Recent studies reported that a series elastic element in skeletal muscle could contribute to large eccentric muscle force production^{23,24}. In the present study, passive stiffness of hamstring, which was calculated based on the passive tension, was associated with the eccentric peak knee flexion torque. Total muscle tension consists of the active tension produced by a contractile element and passive tension produced by a series elastic element. As the muscle fiber is stretched to a longer length, passive tension begins to contribute to the decrement of active tension and allows for a broad range of total muscle tension over a wide range of muscle lengths^{25,26}. During an eccentric contraction, the muscle-tendon unit is lengthened; therefore, passive tension plays a large role in the total muscle force. Higher passive stiffness indicates a higher rate of increase in passive tension as the muscle is lengthened. Accordingly, skeletal muscle with higher passive stiffness can produce a greater total muscle force at a longer muscle length during eccentric contraction.

Ryan et al. (2009) revealed a positive correlation between muscle cross-sectional area (CSA) and passive stiffness in plantar flexor muscle²⁷. Considering this report, in the present study, the CSA of the hamstring might influence the relationship between passive stiffness and peak torque angle. Future studies should examine the relationship between CSA and passive stiffness of the hamstring, and whether the CSA in the hamstring is correlated with the peak torque angle during eccentric knee flexion.

Previous studies reported that greater eccentric hamstring strength^{6,7} and production of larger muscle force at longer muscle lengths^{8,9} might decrease the risks of hamstring strain injury. In the present study, higher passive stiffness of hamstring was associated with peak eccentric knee flexion torque and greater eccentric knee flexion torque at longer muscle lengths. Passive stiffness is considered to express the viscoelasticity of the muscle-tendon unit^{28,29}. Accordingly, these results suggest that the hamstring, which has higher viscoelasticity, can exert greater eccentric muscle force and can endure eccentric overstretching; as a result, it might be less susceptible to hamstring strain injury. Although it has become obvious that a smaller ROM (less flexibility) is not related to the risk of hamstring strain injury^{30,31}, only a few studies have previously reported on the relationship between passive stiffness (viscoelasticity) of the hamstring and the risk of hamstring strain injury³². Accordingly, a future study should examine whether or not enhancing passive stiffness could decrease the incidence of hamstring strain injury. Plyometric exercise increases the muscle force and muscle-tendon stiffness^{33,34}. However, the acute and chronic effect of plyometric exercise on peak torque angle, and the usefulness of the plyometric exercise for prevention of hamstring strain injury are not apparent. These issues are an interesting matter for future study.

Methodological considerations should be addressed. First, we recruited ordinary college students without regular lower limb resistance training. Several weeks of eccentric hamstring training shifts the peak torque angle to a longer muscle length^{35,36}. Athletes perform high-intensity training every day including high-speed running and jumping that require eccentric hamstring contraction. Therefore, athletes have different peak torque angle characteristics from those of ordinary college students. For these reasons, a future study should investigate the association between the passive stiffness of hamstring and peak torque angle during eccentric hamstring contraction in athletes who regularly perform high-speed running and jumping. Second, in this study, we conducted an eccentric hamstring contraction, not in the same position as a passive stiffness measurement, but in the prone position. This is because performing the eccentric hamstring contraction at the same position as the passive stiffness measurement can make it difficult to exert the contraction torque and lead to the risk of muscle injury. Therefore, the hamstring cannot adopt the fully lengthened position during eccentric hamstring contraction, and it cannot be observed how much the passive torque is involved in the eccentric knee flexion torque recorded at each angle. In a future study, the optimal position for measurement should be examined to determine the relationship between the eccentric knee flexion torque at a longer muscle length and passive stiffness.

In conclusion, we showed that passive stiffness of hamstring was associated with the production of greater eccentric knee flexion torque at a longer muscle length. Our finding suggests that the passive stiffness of hamstring may be one of the critical factors in adjusting the peak torque angle condition to achieve lower susceptibility to hamstring strain injury.

Conflict of Interests

All authors declare no conflict of interests.

Author Contributions

Experiment conception and design: SN, SK, KM, SM. Experiment implementation: SN and KM. Data analysis: SN. Paper composition: SN. Analyzing and writing advisory: SK and SM. All authors approved the final version of the manuscript.

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