Effects of dynamic stretching velocity on joint range of motion, muscle strength and subjective fatigue

Abstract

The purpose of this study was to determine the effects of two different dynamic stretching (DS) velocities on joint range of motion (ROM), isometric muscle strength, and subjective fatigue during DS. Fifteen healthy male subjects performed DS at two different velocities: maximal active ankle plantarflexion-dorsiflexion velocity (DS100), and 50% of maximal velocity (DS50). A passive dorsiflexion test and isometric maximal voluntary contractions (MVC) of the ankle plantar flexors and dorsiflexors were performed before and after DS. During the passive dorsiflexion test, ankle ROM and passive torque were measured when the ankle was passively dorsiflexed at 1°/s to its maximal ROM. The DS consisted of four sets of 10 ankle plantarflexions/dorsiflexions. For DS100, participants flexed and extended their ankle as quickly as possible, whereas for DS50 the rhythm of the DS was controlled by a metronome. Subjective fatigue during DS was assessed using a visual analogue scale. Maximal ankle ROM and passive torque at the maximal dorsiflexion angle were significantly increased after both DS100 and DS50 ($P < 0.05$), although there was no significant difference between these trials. The passive torque at submaximal angles and the isometric MVC of the ankle plantar flexors and dorsiflexors were not changed in either condition. However, there was a greater difference in subjective fatigue from pre-stretching to after four sets after DS100 than DS50 ($P < 0.05$).

These results indicate that DS velocity did not influence subsequent joint flexibility. However, DS of moderate speed is recommended, because faster DS appears to be associated with greater fatigue.

Keywords: isometric contraction, passive torque, joint flexibility, electromyography

INTRODUCTION

Dynamic stretching (DS), which involves moving the limbs by contracting the muscle group that is antagonistic to the target muscle group without bouncing (21), has been reported to improve muscle strength (19), vertical jump height (7), sprint time (9), leg power (22), agility time (9), and joint range of motion (ROM) (14). Based on these previous findings, DS is typically performed in warm-up routines before exercise. A small number of recent studies have investigated optimal protocols for DS to improve explosive performance (2, 21). Fletcher (2) focused on the velocity at which DS is performed, reporting that fast DS was associated with greater jump height, compared with slow DS. In addition, Yamaguchi and Ishii (21) reported an optimal protocol for DS to improve explosive performance. This study indicated that 1) for velocity, DS should be performed as quickly as possible, 2) for duration, DS should be performed with 10–15 repetitions × 1–2 sets (21). However, a recent review article concluded that the effects of DS velocity, DS amplitude and DS duration on subsequent muscular performance have not been fully elucidated (16).

An optimal protocol for DS to improve joint flexibility has also not been fully established. A small number of previous studies investigated the effects of DS amplitude

and DS duration on joint flexibility. One previous study reported that the maximal ankle dorsiflexion angle was not increased after 15 repetitions of DS, but increased after four sets of 15 repetitions and seven sets of 15 repetitions of DS (10). It was also reported that DS at maximal amplitude (i.e., DS at maximal active plantarflexion-dorsiflexion ROM) increased the maximal ankle dorsiflexion angle, although no change was seen after DS at 80% maximal active ROM (11). However, no previous study has clarified the effects of DS velocity on joint flexibility. Therefore, to establish an optimal protocol for DS, the effect of DS velocity on joint flexibility requires further investigation.

It is currently unclear whether higher velocity DS should be recommended for increasing joint flexibility, similarly to the situation for increasing jump height reported in a previous study (2). Previous studies have demonstrated that DS improved muscular performance accompanied by an increase in electromyography (EMG) amplitude (2, 4, 19). The increase in EMG activity after DS suggests that neuromuscular mechanisms, especially post-activation potentiation, are responsible for the subsequent improvement in muscular performance (2, 19). Fletcher also proposed that higher velocity movements during fast DS cause an increase in EMG activity during jumping performance, although EMG activity after slow DS did not change (2). Thus, higher velocity DS is more effective

for increasing motor neuron excitability demonstrated by increased EMG. As a result, force output and explosive performance were increased (2). However, muscle relaxation is thought to be important for increasing joint flexibility (12). Therefore, to increase joint flexibility, increases in motor neuron excitability exhibited by increases in EMG activity might be unrelated or even detrimental. Given this background, the aim of the current study was to determine the effects of two different DS velocities on joint ROM and isometric muscle strength, to test the hypothesis that DS velocity does not affect DS-induced changes in joint ROM. The results of this study could contribute to establishing an optimal protocol, and could provide beneficial information for athletes, coaches and therapists.

METHODS

Experimental Approach to the Problem

The subjects visited the laboratory on three occasions, each separated by more than 24 h. The first visit involved a familiarization trial and the subsequent two visits included the following experimental trials: a) DS at maximal active ankle plantarflexion-dorsiflexion velocity (DS100); b) DS at 50% of maximal velocity (DS50). DS100 was conducted before DS50. During the familiarization trial, each subject practiced the passive-

dorsiflexion test and DS to minimize any potential learning effects and to adjust to the procedures. During the experimental trials, the subjects underwent passive-dorsiflexion tests and isometric maximal voluntary contractions (MVC) of the ankle plantar flexors and dorsiflexors before and after DS.

Subjects

Fifteen healthy male subjects volunteered to participate in this study (mean ± SD; age = 20.5 ± 1.1 years, height = 169.6 ± 4.8 cm, weight = 61.8 ± 7.9 kg). No subjects reported any history of recent musculoskeletal injuries or neuromuscular diseases specific to the lower limbs. All subjects were fully informed of the purposes, procedures, and potential risks of the study. Each subject gave written informed consent for participation in the experiments, which were conducted according to the principles set out in the Declaration of Helsinki and approved by the Local Ethics Committee of Nagoya University.

Procedures

Passive-dorsiflexion test

To determine passive torque and ankle ROM, each subject underwent two passive-dorsiflexion tests before and after DS. The passive-dorsiflexion test was performed using

an approach similar to that described in previous studies (13, 15). Subjects were secured on an isokinetic machine (S-15177; Takei Scientific Instruments, Niigata, Japan) with the right knee at full extension and the footplate affixed to the right foot. The angle of the back of the seat was 75° in relation to the floor. In this study, all reported ankle angles refer to the angle of the footplate, and the ankle angle was defined as 0° when the footplate was perpendicular to the floor. Values were defined as positive for dorsiflexion. Ankle ROM was assessed by passively and isokinetically dorsiflexing the subject's foot at a rate of 1°/s from −30° to the angle at which the subject felt discomfort and stopped the dynamometer. The maximal angle of the footplate was defined as the ankle ROM. Throughout the passive-dorsiflexion test, the subjects were asked to completely relax, and to not offer any voluntary resistance. The greater value during the two passive-dorsiflexion tests was used in all subsequent analyses. Passive torque and ankle angle were converted from analogue to digital values at a sampling rate of 1.0 kHz (PowerLab 16SP; PowerLab System, AD Instruments Pty Ltd., Australia).

During this test, the passive torque generated on the footplate was determined, and assessed at submaximal dorsiflexion angles and at the maximal dorsiflexion angle. As with the previous study (17), the submaximal passive torque was assessed at every

fourth degree during the final 13° (at 1°, 5°, 9°, and 13°) common to both assessment periods (pre and post DS).

Isometric maximal voluntary contraction measurement

To determine isometric MVC of the ankle plantar flexors and dorsiflexors, each subject performed ankle plantarflexion and dorsiflexion before and after DS. Subjects were secured on an isometric machine (S-17199; Takei Scientific Instruments, Niigata, Japan) with the right knee at full extension, the footplate fixed to the right foot, and arms crossed in front of the chest. The angle of the back of the seat was 75° in relation to the floor and the angle of the footplate was perpendicular to the floor. The subjects were instructed to perform a 5-sec isometric MVC of plantar flexors and dorsiflexors, twice each. Between each contraction, there was a 1 min rest period. The greater value from the two measurements was used in all subsequent analyses.

Dynamic stretching

Four sets of 10 DS with 30 sec rest between each set were administered to the right lower leg. Each subject was instructed to stand with the knee fully extended and raise the foot from the floor. Subjects then performed active plantarflexion-dorsiflexion in as wide a

range as possible. In DS100, subjects plantarflexed and dorsiflexed their ankle as quickly as possible, in accordance with the recommendations reported in a previous study (21). In DS50, the rhythm of the DS was set as 50% of DS100 and was controlled by a metronome. In the pilot study, subjects were exhausted after performing the DS100. Previous studies reported that DS-induced fatigue impairs subsequent exercise performance (18, 20). Thus, the current study sought to determine a velocity that did not induce fatigue in a pilot experiment, and established a level of 50% of DS100. The ankle angle during DS was measured using an electrical goniometer (DL-210; S&ME, Tokyo, Japan). The level of subjective fatigue induced by DS was also recorded using a 10-cm visual-analogue scale before and after each set. In addition, the difference in subjective fatigue from pre-stretching to after four sets was calculated.

Electromyography

During the isometric MVC measurement, the EMG activity of the gastrocnemius medialis (MG) and tibialis anterior (TA) muscles was measured. This was done using bipolar, disposable surface electrodes (DL-140; S&ME, Tokyo, Japan) placed over the most prominent bulge of the MG and at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus with a 20-mm interelectrode distance. EMG activity was recorded

at a bandwidth of 5–500 Hz. EMG signals were transmitted to a digital data recorder at a sampling rate of 1.0 kHz. In this study, the EMG amplitudes with a period of 0.5-sec before and after the greatest value of isometric MVC were calculated using a root mean square function. In addition, EMG standardization was performed using pre-stretching values for each trial.

Data reliability

Test-retest reliability was calculated using data from two pre-stretching assessments for DS50. Intraclass correlation coefficients (ICCs (2, 1)) and standard errors of measurement (SEMs) were calculated to represent the relative and absolute consistencies for each variable, respectively. The ICC values for ankle ROM, passive torque at maximal dorsiflexion angle, isometric MVC of plantar flexors and isometric MVC of dorsiflexors were 0.984 ($P < 0.001$), 0.935 ($P < 0.001$), 0.926 ($P < 0.001$) and 0.980 ($P < 0.001$), respectively, and the SEM values were 1.3°, 2.6 Nm, 6.1 Nm and 0.8 Nm, respectively. In addition, there were no significant differences between measurements taken during two pre-stretching assessments for ankle ROM ($t = 0.03$, $P = 0.977$), passive torque at maximal dorsiflexion angle ($t = -1.17$, $P = 0.259$), isometric MVC of plantar flexors ($t = 1.78$, $P = 0.097$), and isometric MVC of dorsiflexors ($t = -0.11$, $P = 0.912$).

Statistical analyses

All statistical analyses were performed using SPSS version 22.0 (SPSS, Inc., Chicago, IL, USA). In this study, all measurement parameters were assumed to show normal distribution. Homogeneity of the variances of the difference scores between levels of a repeated measures factor was assessed by the assumption of sphericity. Parameters that did not meet the assumption of sphericity were corrected for this violation using the Greenhouse-Geisser adjustment. A three-way repeated-measures analysis of variance (ANOVA; time [pre or post] × condition [DS100 or DS50] × angle [final1°, final5°, final9°, final13° or maximal dorsiflexion angle]) was used to analyze the passive torque. A two-way repeated-measures ANOVA (time [pre or post] × condition [DS100 or DS50]) was used to analyze the ankle ROM, the isometric MVC and the EMG amplitudes from MG and TA. A two-way repeated-measures ANOVA (set [pre, one set, two sets, three sets or four sets] × condition [DS100, or DS50]) was used to analyze subjective fatigue pre and after each set. A two-way repeated-measures ANOVA (set [one set, two sets, three sets or four sets] × condition [DS100, or DS50]) was used to analyze DS velocity, maximal plantarflexion angle during DS, maximal dorsiflexion angle during DS and ROM during DS. A paired *t*-test was used to analyze the difference in subjective fatigue

from pre-stretching to after four sets between DS100 and DS50. Partial eta squared (η_p^2) values were calculated from the main effects or interactions in the repeated-measures ANOVA, with values of 0.01, 0.06 and above 0.14 representing small, medium and large differences, respectively (1). When significant main effects or interactions were appropriate, follow-up analyses were performed using lower-order repeated-measures ANOVA and *t*-tests with Bonferroni correction. Effect sizes were calculated for pair-wise comparison using Cohen's *d*, defined as small ($d < 0.4$), moderate ($0.41 < d < 0.7$), or large ($0.8 < d$) magnitudes of change (1). Differences were considered statistically significant at $P \leq 0.05$. All data are reported as means ± SD.

RESULTS

DS velocity

There was a significant two-way interaction between set and condition for DS velocity ($F_{(1.834, 25.681)} = 15.914$, $P < 0.001$, $\eta_p^2 = 0.532$). Post hoc testing with Bonferroni-corrected paired *t*-tests revealed that DS velocity during DS100 was greater than that during DS50 in all sets (one set; $P < 0.001$, $d = 2.02$, two set; $P < 0.001$, $d = 2.22$, three set; $P < 0.001$, $d = 2.34$, and four set; $P < 0.001$, $d = 2.39$). In addition, DS velocity during DS100 was faster after three and four sets than that at one set (vs three sets; $P = 0.002$, $d = 0.5$, vs

four sets; $P = 0.001$, $d = 0.62$) and two sets (vs three sets; $P = 0.005$, $d = 0.21$, vs four sets; $P = 0.004$, $d = 0.32$) (Table 1).

Maximal plantarflexion angle, maximal dorsiflexion angle and ROM during DS

There was no significant interaction between set and condition for maximal plantarflexion angle during DS ($F_{[3, 39]} = 0.066$, $P = 0.978$, $\eta_p^2 = 0.005$). In addition, no significant main effects were detected for set ($F_{[1.726, 22,435]} = 0.313$, $P = 0.703$, $\eta_p^2 = 0.024$) or condition ($F_{[1, 13]} = 0.236$, $P = 0.635$, $\eta_p^2 = 0.018$) (Table 1).

There was a significant two-way interaction between set and condition for maximal dorsiflexion angle during DS ($F_{[25.576, 1.967]} = 8.421$, $P = 0.002$, $\eta_p^2 = 0.393$). Post hoc testing with Bonferroni-corrected paired *t*-tests revealed that maximal dorsiflexion angle during DS50 at two ($P = 0.034$, $d = 0.55$), three ($P = 0.027$, $d = 0.41$) and four sets ($P = 0.009$, $d = 0.50$) were greater than that during DS100. In addition, maximal dorsiflexion angle during DS100 was greater after one set than that at two ($P = 0.007$, $d = 0.27$), three ($P < 0.001$, $d = 0.36$) and four sets ($P < 0.001$, $d = 0.52$), and greater after two sets than that after three ($P = 0.034$, $d = 0.09$) or four sets ($P = 0.012$, $d = 0.23$) (Table 1).

There was no significant interaction between set and condition for ROM during DS ($F_{[3, 39]} = 1.873$, $P = 0.150$, $\eta_p^2 = 0.126$). In addition, no significant main effect was detected for condition ($F_{[1, 13]} = 0.2673$, $P = 0.126$, $\eta_p^2 = 0.171$), whereas a significant main effect was observed for set ($F_{[3, 39]} = 6.211$, $P = 0.001$, $\eta_p^2 = 0.323$). However, post hoc testing with Bonferroni-corrected paired *t*-tests revealed that there was no significant difference among sets (Table 1).

Table 1 about here

Ankle ROM

There was no significant interaction between time and condition for ankle ROM ($F_{[1, 14]} = 1.349$, $P = 0.265$, $\eta_p^2 = 0.088$). In addition, no significant main effect was detected for condition ($F_{[1, 14]} = 1.226$, $P = 0.287$, $\eta_p^2 = 0.081$), whereas a significant main effect was found for time ($F_{[1, 14]} = 13.779$, $P = 0.002$, $\eta_p^2 = 0.496$). Post hoc testing with Bonferroni-corrected paired *t*-test revealed that ankle ROM was increased after DS ($P = 0.002$, $d = 0.60$) (Figure 1a, b).

Figure 1 about here

Passive torque

No significant three-way interaction was found among time, condition, and angle ($F_{[1.355, 18.968]} = 0.974$, $P = 0.363$, $\eta_p^2 = 0.065$). In addition, no significant two-way interactions were found between time and condition ($F_{[1, 14]} = 0.802$, $P = 0.386$, $\eta_p^2 = 0.054$), condition and angle ($F_{[1.752, 24.532]} = 1.455$, $P = 0.252$, $\eta_p^2 = 0.094$), whereas a significant two-way interaction was detected between time and angle ($F_{[1.197, 16.764]} = 9.250$, $P = 0.005$, $\eta_p^2 = 0.398$). Post hoc testing with Bonferroni-corrected paired *t*-tests revealed that the passive torque at maximal dorsiflexion angle was increased after DS ($P = 0.010$, $d = 0.94$) (Table 2).

Table 2 about here

Isometric MVC

There was no significant interaction between time and condition for isometric MVC of the plantar flexors ($F_{[1, 14]} = 0.296$, $P = 0.595$, $\eta_p^2 = 0.021$). In addition, no significant main effect was detected for time ($F_{[1, 14]} = 1.567$, $P = 0.231$, $\eta_p^2 = 0.101$) and condition ($F_{[1, 14]} = 3.250$, $P = 0.093$, $\eta_p^2 = 0.188$) (Figure 2a, b).

Figure 2 about here

There was no significant interaction between time and condition for isometric MVC of the dorsiflexors ($F_{[1, 14]}$ = 1.868, P = 0.193, η_p^2 = 0.118). In addition, no significant main effect was detected for condition ($F_{[1, 14]}$ = 0.638, P = 0.438, η_p^2 = 0.044) and time ($F_{[1, 14]}$ = 3.373, P = 0.088, η_p^2 = 0.194) (Figure 3a, b).

Figure 3 about here

EMG during isometric MVC measurement

There was no significant interaction between time and condition for the EMG from MG ($F_{[1, 14]}$ = 0.056, P = 0.817, η_p^2 = 0.004) and TA ($F_{[1, 14]}$ = 0.028, P = 0.871, η_p^2 = 0.002) during isometric MVC of plantar flexors, and no significant main effect was detected for time from MG ($F_{[1, 14]}$ = 1.589, P = 0.228, η_p^2 = 0.102) and TA ($F_{[1, 14]}$ = 0.270, P = 0.611, η_p^2 = 0.019). In addition, no significant main effect was detected for condition for EMG from MG ($F_{[1, 14]}$ = 0.056, P = 0.817, η_p^2 = 0.004), and TA ($F_{[1, 14]}$ = 1.260, P = 0.280, η_p^2 = 0.083) (Table 3).

There was no significant interaction between time and condition for the EMG from MG ($F_{[1, 14]}$ = 2.878, P = 0.112, η_p^2 = 0.171) and TA ($F_{[1, 14]}$ = 0.676, P = 0.425, η_p^2 = 0.046) during isometric MVC of dorsiflexors, and no significant main effect was

detected for condition from MG ($F_{[1, 14]} = 3.160$, $P = 0.097$, $\eta_p^2 = 0.184$) and TA ($F_{[1, 14]} = 0.676$, $P = 0.425$, $\eta_p^2 = 0.046$). In addition, no significant main effect was detected for time for EMG from TA ($F_{[1, 14]} = 1.754$, $P = 0.207$, $\eta_p^2 = 0.111$), whereas a significant main effect was seen for the EMG from MG ($F_{[1, 14]} = 5.540$, $P = 0.034$, $\eta_p^2 = 0.284$) (Table 3).

Table 3 about here

Subjective fatigue

There was a significant two-way interaction between set and condition for subjective fatigue after each set ($F_{[16.313, 1.165]} = 7.255$, $P = 0.013$, $\eta_p^2 = 0.341$). Post hoc testing with Bonferroni-corrected paired *t*-tests revealed that subjective fatigue during DS100 was greater after four sets of DS100 compared with pre-stretching ($P = 0.024$, $d = 10.77$); greater after three sets of DS100 compared with pre-stretching ($P = 0.004$, $d = 5.96$), one ($P = 0.025$, $d = 3.57$) and two sets ($P = 0.038$, $d = 2.00$); and greater after one ($P = 0.009$, $d = 1.76$) and two sets ($P = 0.002$, $d = 3.10$) of DS100 compared with pre-stretching. In addition, subjective fatigue during DS50 was greater after three sets of DS50 than after one ($P = 0.033$, $d = 1.24$) or two sets ($P = 0.008$, $d = 0.64$) of DS50 (Figure 4a, b).

There was a significant difference between DS100 and DS50 in the difference in subjective fatigue from pre-stretching to after four sets (t = 2.853, P = 0.013, d = 0.80) (Figure 4c).

Figure 4 about here

DISCUSSION

The purpose of this study was to determine the effects of changes in DS velocity on ankle ROM, isometric muscle strength, and subjective fatigue. The results revealed that differences in the increment of ankle ROM were not dependent on DS velocity, although ankle ROM was increased after both DS trials. In addition, the findings suggested that the isometric MVC of the plantar flexors and dorsiflexors were unchanged after both DS trials. However, the difference in subjective fatigue from pre-stretching to after four sets was greater during DS100 than that during DS50.

In accordance with the study hypothesis, the DS-induced increment in ankle ROM was not affected by DS velocity. The present findings demonstrated that ankle ROM was increased after both DS velocities (approximately 1.0° increment after DS100, and approximately 2.1° increment after DS50). The increase in ankle ROM after DS50

was similar to that reported in previous studies (10, 11, 14, 18), whereas the increase after DS100 was less than that reported in previous studies. However, because there was no significant difference in the increase in ROM between trials, the results indicated that there was no effect of DS velocity on increase in ankle ROM. In contrast to the current findings, a previous study investigating the effects of DS velocity on jump performance reported that fast DS induced a greater improvement of jump height than slow DS (2). The results of that study also revealed a greater increase in the EMG amplitude of the lower limb muscles during jumping, leading the author to conclude that a greater increase in jump height after fast DS was due to an increase in motor neuron excitability (2). In contrast, several previous studies focusing on the involvement of the central nervous system in joint flexibility reported that inhibition of the excitability of the primary motor cortex and/or the primary somatosensory cortex by transcranial direct current stimulation increased joint ROM (5, 8, 12). Taken together, these studies suggest the importance of increasing joint flexibility to inhibit motor neuron excitability rather than promote it (5, 8, 12. Therefore, DS100 did not induce an additional increase in ankle ROM compared with DS50.

The absence of change in isometric MVC observed in the current study is likely

to be related to the accumulation of DS-induced fatigue. As reported in a recent review article, most previous studies reported significant DS-induced increases in force and power, or no adverse effects, although a small number of previous studies reported a significant decrease in force after DS (16, 21). Several mechanisms have been proposed to explain DS-induced performance enhancement. Fletcher and Monte-Colombo (3) reported that DS increased heart rate in addition to jump height and peak torque compared with static stretching and no-stretching warm-up. The authors concluded that increased heart rate could potentially be an underlying mechanism of DS-induced enhancement of performance (3). Post-activation potentiation has also been suggested as a potential mechanism by which DS improves exercise performance (2, 19, 22). In addition, a small number of previous studies have attributed DS-induced effects to neural adaptation, such as greater motor unit activation reflected in EMG augmentation after DS (2, 19). However, in contrast to the above explanation, post-activation potentiation and increased EMG amplitude were not observed in the current study, although heart rate was not measured. Rather, DS-induced fatigue appeared to be the factor that disturbed the DS-induced improvement. Turki et al. (20) demonstrated that 20-m sprint time was improved after one and two sets of DS, whereas sprint time was impaired after three sets of DS. Thus, the authors raised the possibility that three sets of DS could induce acute fatigue and

impair sprint performance, but unfortunately did not estimate fatigue of subjects (20). The current results indicated that subjective fatigue during DS was increased as the number of sets increased, in both conditions. Because the DS duration used in the current study was based on the optimal duration for improving joint ROM (10), it was slightly greater than that previously recommended for improving explosive performance (21), so excessive DS would be expected to induce fatigue. Therefore, this type of fatigue may have been a reason for the lack of improvement in isometric MVC after DS.

Moderate DS velocity is recommended for improving joint ROM, because DS100 increased subjective fatigue without an additional improvement in joint flexibility. The difference in subjective fatigue from pre-stretching to after four sets after DS100 was more than twice that of DS50. This increment in subjective fatigue was due to the increment of DS velocity. Thus, DS velocity appears to be one of the factors increasing DS-induced fatigue, similar to DS duration and DS amplitude (11, 20). Impairment of exercise performance by DS-induced fatigue is a serious problem (18, 20). In addition, it is possible that the decrease in maximal dorsiflexion angle during DS observed in DS100 diminishes the DS-induced increment of joint ROM (11). Thus, if the aim of DS is to improve joint ROM, the current study suggests that moderate DS velocity is appropriate.

However, contrary to this recommendation, Fletcher et al. (2) recommended that fast DS should be performed to improve jump performance. These differences in recommendations between the two studies may be related to the definition of DS velocity. In the current study, the velocity of DS100 was defined as joint movement with maximal effort, whereas fast DS was defined as 100 beats/min in the previous study (2). Thus, each velocity was substantially different (170 beats/min in this study vs 100 beats/min in the previous study) (2). Instead, the velocity of DS50 (86 beats/min) was similar to fast DS in the previous study rather than DS100 (2). Therefore, the current findings suggest that DS should be performed with moderate velocity, such as 86 to 100 beats/min, regardless of whether the purpose is to improve joint flexibility or jump performance.

The increase in ankle ROM after DS is likely to be due to an increase in stretch tolerance. Previous studies explained that the increase in ankle ROM after DS was caused by changes in mechanical factors such as stiffness or passive torque and neural factors such as stretch tolerance (6, 14). The present study indicated that passive torque at maximal dorsiflexion angle was significantly increased after DS, suggesting a change in neural factors (increased stretch tolerance). In contrast, passive torque during the final 13° was not changed, indicating no change in mechanical factors. Thus, the increase in

ankle ROM after DS appeared to be due to an increase in stretch tolerance in the current study.

The present study involved an important limitation that should be considered. Because the velocity of the DS50 was set as 50% of DS100, the DS100 trial had to be conducted before the DS50 trial. Thus, the possibility that differences in subjective fatigue between trials resulted from an order effect cannot be eliminated.

In conclusion, the current study demonstrated that there was no effect of DS velocity on the increment of joint flexibility, although DS increased joint flexibility. However, DS100 induced greater subjective fatigue than DS50. These results suggest that performing DS with a moderate speed should be recommended to improve joint flexibility without fatigue.

PRACTICAL APPLICATIONS

Identifying an optimal DS protocol for improving joint flexibility is an important issue. Previous review article have identified several influential DS variables, including stretching duration, stretching amplitude and stretching velocity (16). Among these

variables, the current study clarified the effects of stretching velocity, complementing previous studies clarifying the effects of stretching duration and stretching amplitude on joint flexibility (10, 11). Thus, based on these results together, performing DS in four sets of 15 repetitions with maximal amplitude by moderate velocity appears to be the optimal protocol when the purpose of DS is to improve ankle ROM. However, athletes and coaches should have attention that this recommendation would have several important limitations that should be considered. First, it is unclear whether this recommendation applies to joints other than the ankle, because it was evaluated only in the ankle joint. Second, it is not entirely clear whether characteristics of the study population, including gender, age and type of sporting career influenced the effects of DS. At last, because DS is typically performed as part of a warm-up routine, the effects of combining DS with other warm-up exercises, such as running, should be clarified. Thus, further study is clearly needed.

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Figure Legends

Figure 1: Stretching-induced changes in ankle range of motion. (a) Absolute values of ankle range of motion at pre- and post-dynamic stretching for individuals. (b) Differences in ankle range of motion from pre- to post-dynamic stretching for individuals. DS100 and DS50 represent dynamic stretching at maximal active ankle plantarflexion-dorsiflexion velocity and dynamic stretching at 50% of maximal velocity. *Significantly different from pre-stretching ($P < 0.05$). Data are expressed as mean ± SD.

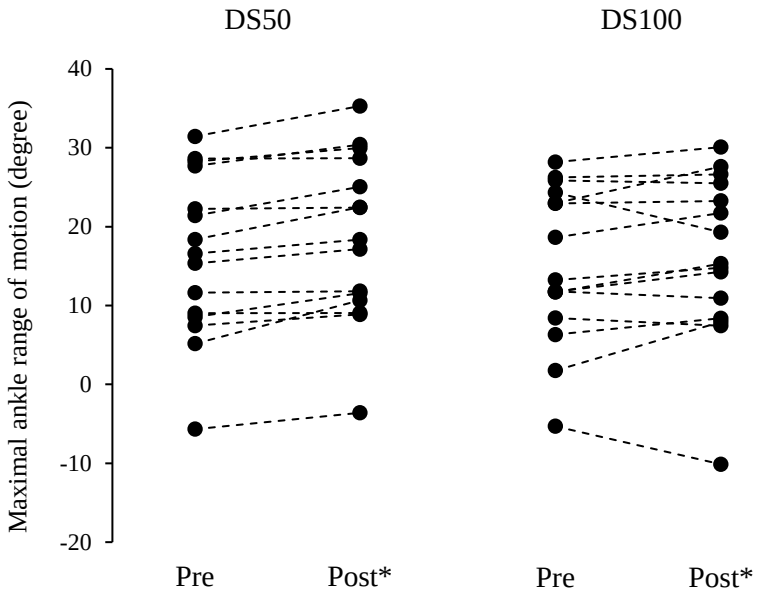
Figure 2: Stretching-induced changes in maximal isometric plantarflexion torque. (a) Absolute values of maximal isometric plantarflexion torque at pre- and post-dynamic stretching for individuals. (b) Differences in maximal isometric plantarflexion torque from pre- to post-dynamic stretching for individuals. DS100 and DS50 represent dynamic stretching at maximal active ankle plantarflexion-dorsiflexion velocity and dynamic stretching at 50% of maximal velocity. Data are expressed as mean ± SD.

Figure 3: Stretching-induced changes in maximal isometric dorsiflexion torque. (a) Absolute values of maximal isometric dorsiflexion torque at pre- and post-dynamic stretching for individuals. (b) Differences in maximal isometric dorsiflexion torque from pre- to post-dynamic stretching for individuals. DS100 and DS50 represent dynamic stretching at maximal

active ankle plantarflexion-dorsiflexion velocity and dynamic stretching at 50% of maximal velocity. Data are expressed as mean ± SD.

Figure 4: Comparisons between conditions for subjective fatigue: (a) stretching-induced changes in subjective fatigue in each set; (b) stretching-induced changes in subjective fatigue in each set for individuals; c) difference in subjective fatigue from pre-stretching to after four sets for individuals. DS100 and DS50 represent dynamic stretching at maximal active ankle plantarflexion-dorsiflexion velocity and dynamic stretching at 50% of maximal velocity. [a]Significantly different from pre of DS100 ($P < 0.05$). [b]Significantly different from one set of DS100 ($P < 0.05$). [c]Significantly different from two sets of DS100 ($P < 0.05$). [d]Significantly different from one set of DS50 ($P < 0.05$). [e]Significantly different from two sets of DS50 ($P < 0.05$). *Significantly different from DS50 ($P < 0.05$). Data are expressed as mean ± SD.

a


DS50
DS100
Maximal ankle range of motion (degree)
40
30
20
10
0
-10
-20
Pre
Post*
Pre
Post*

b

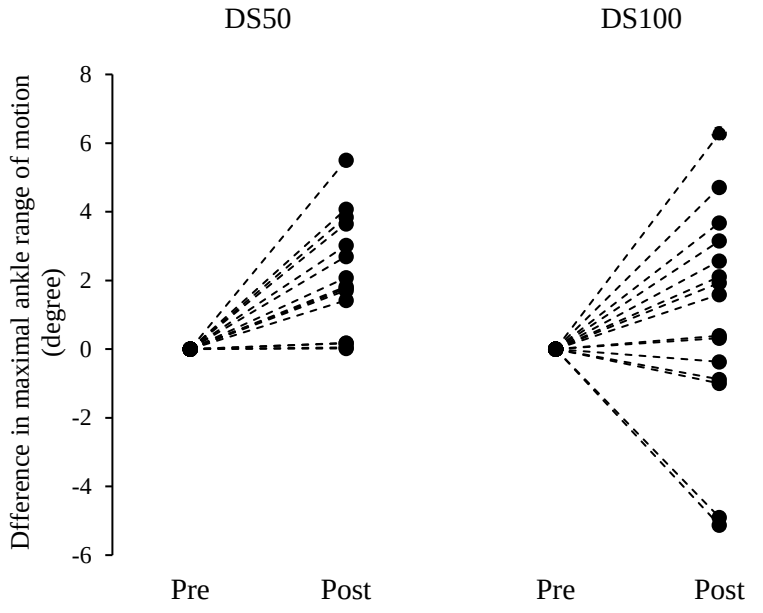
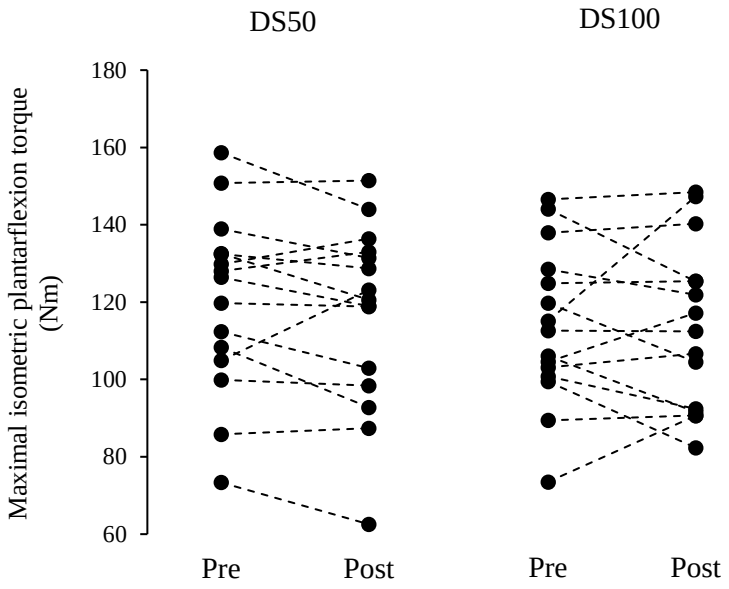

DS50
DS100
Dfference in maximal ankle range of motion (degree)
8
6
4
2
0
-2
-4
-6
Pre
Post
Pre
Post

Figure 1

a


DS50
DS100
Maximal isometric plantarflexion torque (Nm)
180
160
140
120
100
80
60
Pre
Post
Pre
Post

b

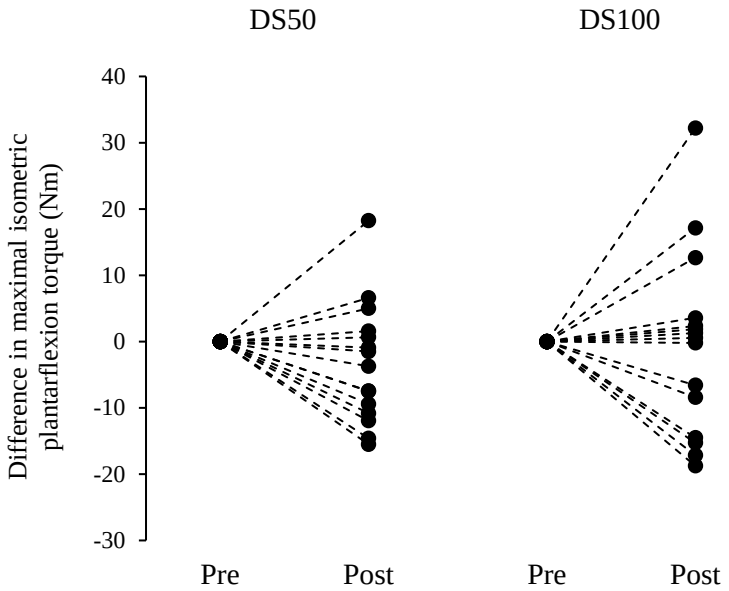
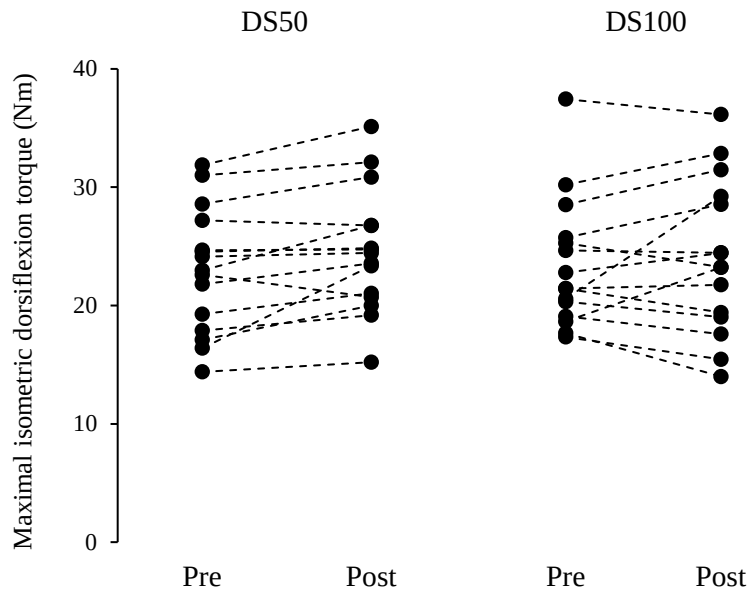

DS50
DS100
Difference in maximal isometric plantarflexion torque (Nm)
40
30
20
10
0
-10
-20
-30
Pre
Post
Pre
Post

Figure 2

a


DS50
DS100
Maximal isometric dorsiflexion torque (Nm)
40
30
20
10
0
Pre
Post
Pre
Post

b

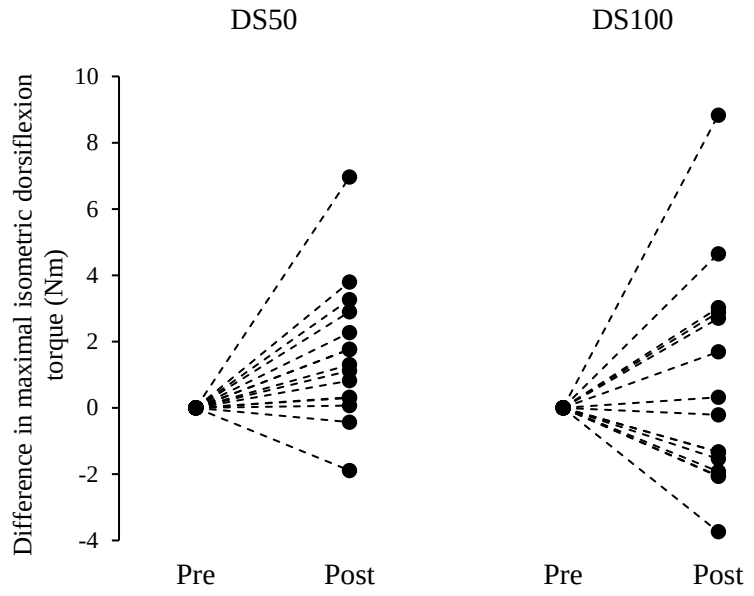
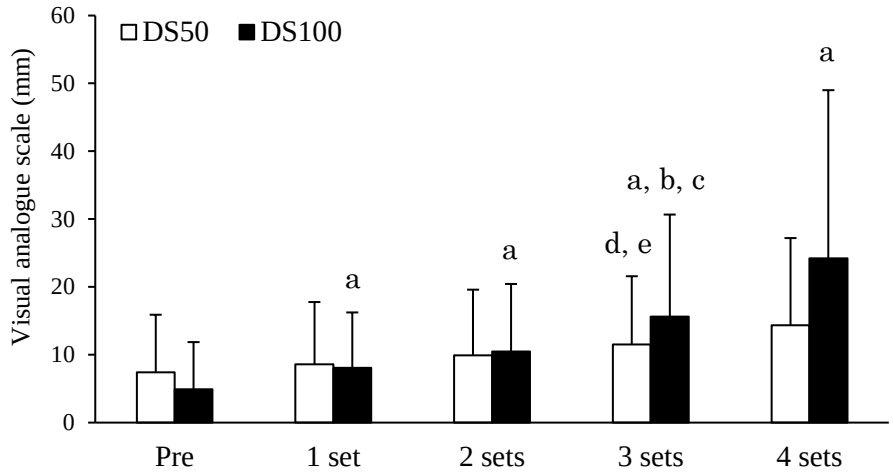
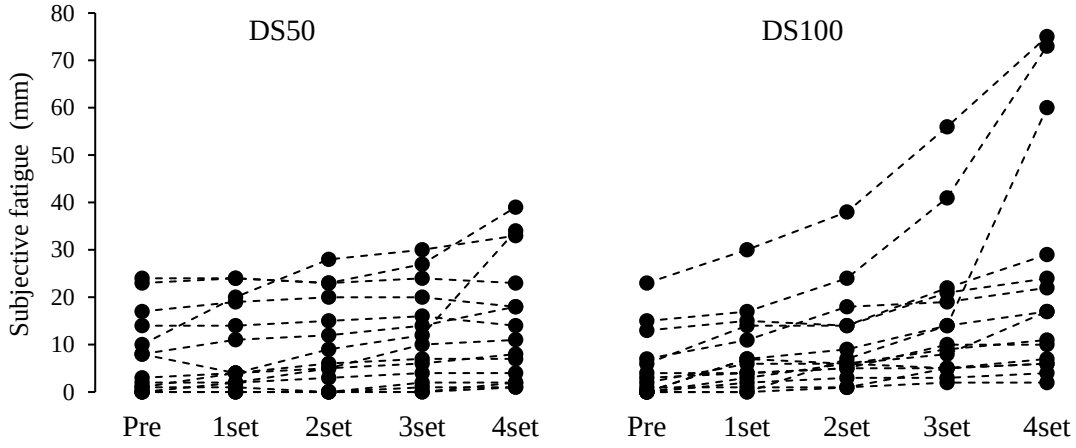

DS50
DS100
Difference in maximal isometric dorsiflexion torque (Nm)
10
8
6
4
2
0
-2
-4
Pre
Post
Pre
Post

Figure 3

a


□DS50 ■DS100
Visual analogue scale (mm)
60
50
40
30
20
10
0
a
a
a, b, c
d, e
a
Pre
1 set
2 sets
3 sets
4 sets

b


DS50
DS100
Subjective fatigue (mm)
80
70
60
50
40
30
20
10
0
Pre
1set
2set
3set
4set
Pre
1set
2set
3set
4set

c

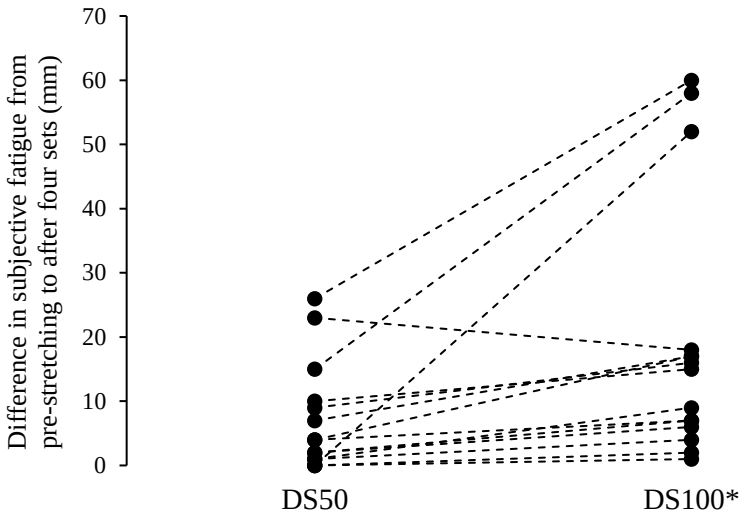

Difference in subjective fatigue from pre-stretching to after four sets (mm)
70
60
50
40
30
20
10
0
DS50
DS100*

Figure 4