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Original Article

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Immediate Effects of Warm-Up Protocols, Including Dynamic Stretching on Explosive Strength of Knee Extensors

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Purpose: Variables, such as torque and power, have been measured to evaluate the muscle function. This study examined the effects of a warm-up protocol, including dynamic stretching (DS), on the explosive strength of knee extensors, as well as torque and power.
Methods: Twenty-nine healthy young adults participated in this study. Three warm-up protocols, including DS of knee extensors, were used as interventions: (1) DS, (2) DS combined with antagonist muscle static stretching (AMSS), and (3) DS combined with repetitive passive movements (RPM). The outcome measures were the following variables of the knee extensors evaluated using an isokinetic dynamometer: rate of torque and velocity development (RTD and RVD), isometric and isokinetic peak torque (PT), and average power (AP).
Results: The results of the two-way (warm-up and time) repeated-measures ANOVA revealed a main effect of time for isometric PT ($p = 0.001$). Post-hoc analysis revealed a significant increase in isometric PT in the post-test compared to the pre-test regarding the DS-AMSS ($p = 0.001$) and DS-RPM ($p = 0.047$) warm-up protocols.
Conclusion: The three warm-up protocols (DS, DS-AMSS, and DS-RPM) do not appear to influence explosive strength and isokinetic strength at a rapid angular velocity. Considering the relatively high volume of DS used in this study, this may be due to the influence of muscle fatigue. These findings suggest that tailored warm-up protocols for fast muscle contraction and joint acceleration, unlike isometric PT corresponding to static contraction, may require a different approach from existing methods.

Keywords: Explosive strength, Warm-up, Dynamic stretching, Knee extensors

INTRODUCTION

Structured warm-ups are used as a pre-exercise routine because they can improve athletic performance.[1] Components of a warm-up primarily include static stretching (SS).[2] SS is considered to position the muscle to its maximum possible length and hold that position.[3] SS has been included in training programs and regular routines before sports activities because it is believed to increase the range of motion (flexibility) around the joints and prevent sports injuries.[2] However, many studies have reported that SS (especially long-term SS) can have detrimental effects on muscular performance.[2,4,5] Therefore, it has been suggested that performing SS before high-level athletic or training activities may be undesirable.[4]

In this regard, an alternative method for preparing for subsequent exercise is dynamic stretching (DS).[6] DS is considered a movement in the entire range of motion with little or no resistance by contracting the antagonist of the target muscle.[6] DS has been reported to improve muscle strength, sprint, and jump performance as well as increase the range of motion around joints without impairing muscle function. However, recent studies have not found positive effects of DS compared to SS on muscle strength or performance.[4,5,7] That is, there are inconsistent results for the effectiveness of DS as part of a warm-up. Based on the effects of SS and DS, studies on the effect of SS applied to antagonists on agonist muscle performance are being investigated.[8-11] However, this also reports inconsistent results similar to DS.

Muscular strength (traditionally measured by peak torque, PT) or muscle mass does not include factors related to muscle contraction velocity.[12] On the other hand, the rate of torque and velocity development (RTD and RVD) may be used to evaluate explosive contraction or joint acceleration related to muscle contraction velocity.[13-15] RTD and RVD refer to the ability to generate force and angular velocity within a limited time, and these vari-

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ables are gaining importance because they widely influence physical functions such as athletic performance, activities of daily life, and prevention of falls.[13] In addition, RTD and RVD have been reported to be more related to functional movement than other variables of muscle function.[16,17]

The reciprocal inhibition (RI) function of spinal neural circuits is well known to be important in movements such as fast and powerful muscle contractions, smooth joint motion, and walking.[18,19] RI is defined as the inhibition of antagonist motor neurons in parallel with the activation of agonist motor neurons during movement.[18] Effective RI can play an important role in activities that require rapid and powerful activation of specific muscles, such as the sprint and jump.[20] Accordingly, interest in RI enhancement strategies has recently increased.[19] Repetitive passive movement (RPM), which is currently widely used as a rehabilitation technique, not only enhances RI but also affects proprioception and cortical excitability (primary somatosensory cortex and the primary motor cortex).[21-23] Consequently, RPM appears to contribute to neuromuscular changes. However, few studies have used this RPM as part of a warm-up.

Studies of the immediate effects of warm-up protocols including DS on RTD and RVD appear to be limited as these variables have received attention from researchers relatively more recently than muscle strength. Therefore, the primary purpose of this study was to determine the effects of DS on traditional isokinetic parameters (torque and power), RTD, and RVD of knee extensors. In addition, considering that RI has a positive effect on explosive muscle strength, this study investigated the effects of DS-combined antagonist muscle SS (DS-AMSS), and DS-combined RPM (DS-RPM), which are expected to enhance RI. Furthermore, the effectiveness of three warm-up protocols (DS, DS-AMSS, DS-RPM) was compared.

METHODS

1. Participants

The sample size required for this crossover design study was calculated using statistical software (G-Power 3.1.9.7, Düsseldorf, Germany). The estimated effect size (ES = 0.33) was based on a systematic review study that investigated the acute effect of DS on physical performance.[24] Statistical power was set at 0.95 with an alpha error probability of 0.05. As a result, the minimum sample size was 22 subjects.

Healthy young adults were recruited for this study. Exclusion criteria were as follows: (1) history of lower extremity or lower back surgery or injury in the past 6 months, (2) cardiovascular or neurological disease, (3) current inflammatory disease, or (4) limited maximal muscle contraction. Additionally, participants who were deemed difficult to participate by the researcher due to physical or mental problems or who were participating in other exercise programs were also excluded. Thirty-two young adults volunteered to participate in this study. Three participants dropped out due to knee pain (n = 1) and loss of data (n = 2). Consequently, data from twenty-nine participants were used for analysis (Table 1). Written informed consent was obtained from all participants. They were also aware of their right to withdraw from this study. The Institutional Review Board of the university approved this study (SM-202109-065-2), which was performed by the principles of the Declaration of Helsinki.

Table 1. General characteristics of participants

Variables	N=29
Sex (male/female)	14/15
Age (year)	24.1±2.7
Height (cm)	168.3±8.7
Body mass (kg)	64.0±10.4
Body mass Index (kg/m^2)	22.5±2.5

Data are presented as mean±standard deviation.

2. Experimental procedures

The experimental procedure is shown in Fig. 1. Participants visited the laboratory three times at intervals of 48–72 hours.[25] Three experimental sessions correspond to (1) DS, (2) DS-AMSS, and (3) DS-RPM. Experimental sessions were administered in a randomized order. In all sessions, participants first performed a warm-up consisting of 3 minutes of aerobic exercise using a cycle ergometer and ten incremental submaximal voluntary contractions of the knee extensors. Five minutes of rest was given between warm-up and pre-test. After a rest period, participants performed a pre-test. Upon completion of the pre-test, participants performed one of three warm-up protocols: DS, DS-AMSS, and DS-RPM. The duration of each protocol was set the same. Finally, the post-test was conducted the same as the pre-test. However, before the post-test, there was no aerobic exercise or submaximal voluntary contraction other than the warm-up protocol, which was used as an intervention. Each participant completed all three warm-up protocols over a total of three visits.

3. Outcome measures

Participants performed 3 minutes of aerobic exercise using a cycle ergometer (1W/kg power output and a crank rate of 60revs/min) as a warm-up before testing.[26] The isometric and isokinetic modes of the isokinetic dy-

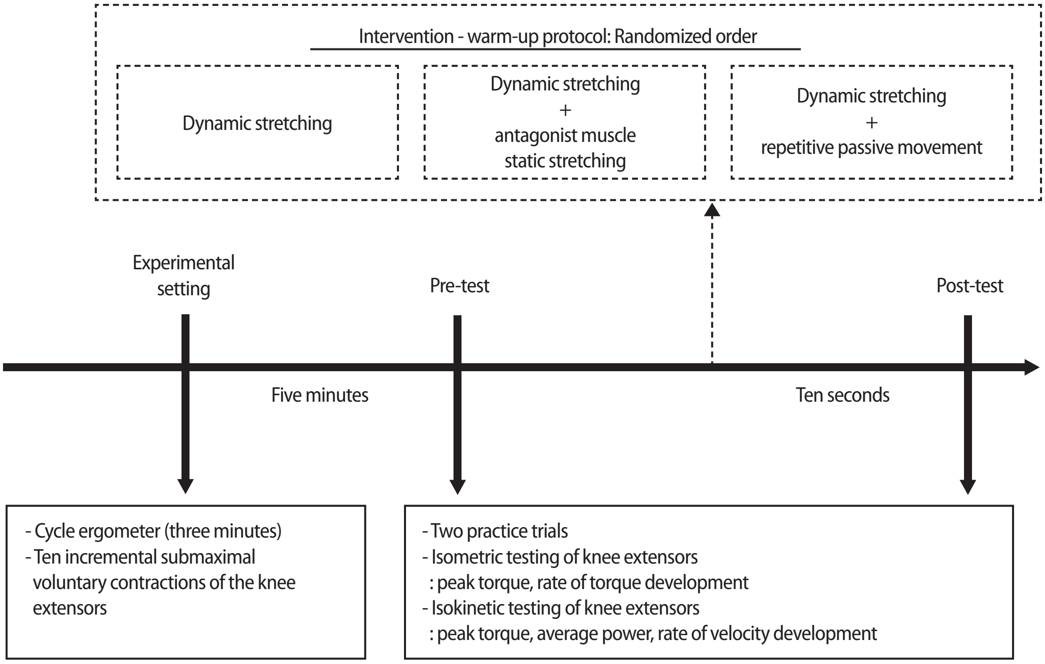

Figure 1. Experimental procedure.

namometer (HUMAC NORM Testing and Rehabilitation System, CSMI Medical Solutions, MA, USA) were used to measure variables related to the muscle function of the knee extensors of the dominant leg (the leg used to kick the ball). Data signals from the dynamometer were sampled and recorded at 100Hz. The order of measurement of the two modes was randomly assigned to each participant. There was a familiarization session of ten incremental submaximal voluntary contractions before measurements in each contraction mode. During the test, the participant was seated in a dynamometer chair and the trunk and thighs were secured using straps. The hip joint angle was maintained at 85° flexion. The dynamometer rotation axis was aligned with the knee lateral epicondyle and the force pad was placed approximately 3cm above the medial malleolus.

PT and RTD were measured in isometric testing. The knee joint position was 70° flexion.[27] Participants were asked to perform three isometric knee extensions for 3 seconds with verbal instructions to push as fast and hard as possible.[12,14] PT (Newton meters, Nm) was represented as the maximum value of the torque released by a muscle contraction and normalized to body weight (Nm/kg).[28] RTD (Nm/s), defined as the slope of the torque-time curve (Δtorque/Δtime), was determined as the onset of contraction when torque increases above 2.5% of PT.[12-14,27] The peak RTD was quantified as the maximum slope of the torque-time curve and was calculated by dividing the time after force onset by the interval of 20 milliseconds (i.e., 0–20, 20–40, 40–60, …, 2,980–3,000ms).[12,13] RTD values (1) 0 to 50 milliseconds (RTD 0–50), (2) 100 to 200 milliseconds (RTD 100–200), (3) peak RTD were used for analysis. The PT and RTD values from the trial with the highest PT were used for analysis.[12]

PT, average power (AP), and RVD were measured in isokinetic testing. The knee range of motion was set from 90° flexion to 0° (knee full extension in voluntary). Participants performed three knee concentric extensions at 240°/s with verbal encouragement from the investigator. In the isokinetic test, 240°/s was mainly regarded as a fast angular velocity, so it was used to measure muscle function at fast velocity.[29] PT (Nm/kg), AP (Watts, W), and RVD values were calculated. AP means work (product of force and distance) divided by unit time. RVD (°/s/s) indicated the slope of the velocity-time curve (Δvelocity/Δtime). For RVD calculation, the start of knee movement was regarded as the point where the angular velocity reached 2°/s, and the endpoint was analyzed up to the point where it reached 2°/s below the target angular velocity (240°/s) (i.e., from 2°/s to 238°/s).[17] The PT, AP, and RVD values of the trial with the highest PT values were used for analysis.[16,17]

4. Intervention

1) Dynamic stretching

For DS of the knee extensors (quadriceps), in a standing position, participants were asked to place one arm next to the trunk and lightly support the other arm against a wall to maintain balance. Then, the participants flexed the knee joint (hamstring contraction) so that the heel touched their buttocks.[30] After reaching the end range, it returned to the starting position without additional holding time. The DS was performed in 3 sets of 20 repetitions each at their self-preferred velocity, with 20 seconds of rest between sets. To match the duration with the DS-AMSS, and DS-RPM protocols, additional DS was performed for about 3–5 minutes (20 repetitions followed by 20 seconds of rest).

2) Dynamic stretching combined with antagonist muscle static stretching

Participants first completed the DS of knee extensors in the same way as the DS protocol. After a rest of 20 seconds, SS of the hamstring (antagonist muscle) was performed. SS was based on the procedure in recent previous studies.[31] For the SS protocol, participants were asked to sit in an isokinetic dynamometer chair and relax during stretching. The knee joint was passively extended at a slow angular velocity (5°/s) from 90° of flexion to the angle at the point of maximum discomfort. The final position was held for 60 seconds. Afterwards, the knee joint was passively returned to the starting position. Five SS were completed with 20 seconds of rest given between each stretching.

3) Dynamic stretching combined with repetitive passive movement

Participants performed stretching of knee extensors in the same manner as in the DS protocol before RPM. After a rest of 20 seconds, the RPM of the knee joint was executed using an isokinetic dynamometer to control the movement's angular velocity and range of motion. The range of motion of RPM was from 90° flexion to 0° (self-reported full extension) and the angular velocity was set to 180°/s. Starting from the 90° flexion position of the knee and returning to the same position was counted as 1 time. Three sets of 100RPM were performed (a total of 300RPM), with a 20-second rest between sets. Participants were asked to focus their attention on the RPM of the knee.[23] In addition, unexpected accidents were prevented by allowing participants to press the emergency stop button.

5. Statistical analysis

All measured data are expressed as mean ± standard deviation. The Shapiro–Wilk test was used to test the normality of the data. A two-way repeated-measures analysis of variances (ANOVA) was used to compare the changes in measured variables according to the warm-up (DS, DS-AMSS, and DS-RPM) × time (pre- and post-test). Bonferroni post hoc pairwise comparisons were conducted in case of significant main effects or interactions. Partial eta squares (partial η^2) representing the effect size for each dependent variable were calculated. Values above 0.01, 0.06, and 0.14 are considered small, medium, and large differences, respectively.[32] The level of statistical significance was set as $p<0.05$. All procedures were performed using SPSS software (SPSS 22.0, Armonk, NY, USA).

RESULTS

Table 2 presented the mean and standard deviation of PT (isometric and isokinetic) and AP of knee extensors before and after three warm-up protocols. According to the results of the two-way repeated-measures ANOVA of warm-up and time, there was a main effect of time for isometric PT [$F(1,28)=15.445$, $p=0.001$, $\eta^2=0.356$]. As a result of the post-hoc analysis, isometric PT was significantly increased in the post-test compared to the pre-test in the DS-AMSS ($p=0.001$) and DS-RPM ($p=0.047$) warm-up protocols (Figure 2). However, no significant main and interaction (warm-up × time) effects were observed in PT and AP during isokinetic contraction at 240°/s ($p>0.05$).

Table 3 shows the results of two-way (warm-up × time) repeated measures ANOVA on RTD and RVD. There was no significant effect on RTD and RVD ($p>0.05$).

Table 2. The results of two-way (warm-up × time) repeated measures for peak torque and average power of knee extensors

Variables		DS	DS-AMSS	DS-RPM	p value (η^2)		
					Warm-up	Time	Interaction
Isometric PT (Nm/kg)	Pre	2.72±0.56	2.69±0.61	2.65±0.55	0.626 (0.017)	0.001 (0.356)	0.694 (0.013)
	Post	2.85±0.64	2.91±0.66	2.78±0.59			
Isokinetic PT at 240°/s (Nm/kg)	Pre	1.19±0.32	1.22±0.31	1.22±0.34	0.945 (0.002)	0.076 (0.108)	0.429 (0.030)
	Post	1.19±0.33	1.18±0.34	1.18±0.36			
AP at 240°/s (Watt)	Pre	132.03±65.49	136.31±57.75	131.35±68.57	0.612 (0.017)	0.333 (0.033)	0.848 (0.006)
	Post	130.48±63.09	130.79±64.23	126.86±63.32			

Data are presented as mean±standard deviation. DS: dynamic stretching, AMSS: antagonist muscle static stretching, RPM: repetitive passive movement, PT: peak torque, AP: average power.

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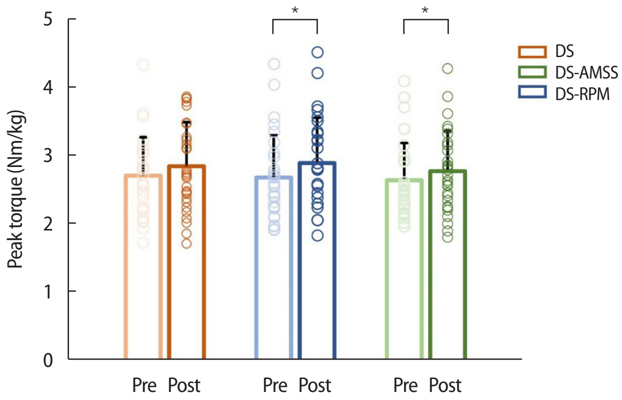

Figure 2. Comparison of isometric peak torque pre and post three warm-up protocols. DS: dynamic stretching, AMSS: antagonist muscle static stretching, RPM: repetitive passive movement. *Significant difference pre- and post- warm-up (DS-AMSS: p=0.001, DS-RPM: p=0.047).

Table 3. The results of two-way (warm-up×time) repeated measures for the rate of torque and velocity development

Variables		DS	DS-AMSS	DS-RPM	p value (η^2)		
					Warm-up	Time	Interaction
RTD 0-50 (Nm/s)	Pre	631.38±343.56	604.34±351.59	606.41±300.89	0.262 (0.047)	0.391 (0.026)	0.326 (0.039)
	Post	668.83±328.69	676.41±366.52	577.31±342.45			
RTD 100-200 (Nm/s)	Pre	461.07±181.19	438.93±190.23	412.38±178.35	0.074 (0.089)	0.052 (0.128)	0.760 (0.010)
	Post	495.62±179.07	481.45±186.24	427.93±160.55			
RTD peak (Nm/s)	Pre	781.55±372.49	760.17±457.17	794.48±347.78	0.684 (0.013)	0.307 (0.037)	0.306 (0.041)
	Post	851.03±397.31	827.24±392.55	766.03±384.68			
RVD (°/s/s)	Pre	868.51±44.99	868.89±50.02	864.17±60.32	0.979 (0.001)	0.095 (0.096)	0.551 (0.021)
	Post	857.07±62.01	853.66±66.81	860.32±59.06			

Data are presented as mean±standard deviation. DS: dynamic stretching, AMSS: antagonist muscle static stretching, RPM: repetitive passive movement, RTD: rate of torque development, RVD: rate of velocity development.

DISCUSSION

This study confirmed the immediate effects of warm-up protocols including DS, DS-AMSS, and DS-RPM on PT, AP, RTD, and RVD. PT was evaluated in both isometric and isokinetic contractions to reflect the static and dynamic contraction of the muscle. The findings of this study were that DS-AMSS and DS-RPM had an immediate effect on isometric PT improvement. However, the warm-up protocol used in this study did not appear to influence immediately isokinetic PT, AP, RTD, or RVD.

DS-AMSS and DS-RPM appear to have acute effects on improving isometric PT. On the other hand, although there was an increasing trend in isometric PT after DS, there was no statistical difference. It has been reported that DS induces improvement in muscle performance due to the increase in temperature, potentiation-related mechanisms, and improvement of nerve conduction velocity by voluntary contractions.[6] SS reduces the excitability of motor neurons and reduces musculotendinous unit (MTU) stiffness, thereby reducing the force transmitted from the muscle to the skeleton.[7,33] Based on the results of these studies, in this study, it was hypothesized that DS-AMSS would induce improvement in the muscle performance of the agonist. Therefore, it seems that the combination of DS (increased nerve activation and temperature) and SS (decreased MTU and nerve impulses) performed for agonist and antagonist, respectively, led to the improvement of isometric PT.

The RPM protocol followed by DS also showed similar results to DS-AMSS. Recent studies have reported that RPM induces the enhancement of RI.[19,21] Faster and wider range RPM is more likely to increase Ia firing, which may enhance RI by activating inhibitory interneurons.[19] Based on these findings, this study used a relatively high angular velocity of 180°/s, and the range of motion was set from full extension to 90° flexion. These findings cautiously suggest the possibility that enhancement of RPM-induced RI along with the effect of DS may be an appropriate conditioning activity to improve isometric PT. However, as there were no measurements of RI, future studies should investigate the mechanism by which RPM affects muscle performance. Additionally, RPM has been shown to modulate the cerebral cortex and corticospinal excitability as well as induce enhancement of proprioception.[22,23,34] However, explanations are difficult in this study because the immediate effect of these mechanisms on muscle performance was not investigated. Finally, considering that active movement is more effective for performance improvement than passive movement, RPM may be appropriate to be used with voluntary contractions (including DS).

In this study, when only DS was performed as a warm-up, no change in muscle function was found. Unlike previous studies that performed DS for several muscle groups, repeated DS was performed on a single muscle in this study. Moreover, additional DS was performed to match the same time with DS-AMSS and DS-RPM. High-volume DS may have negative effects on physical performance.[5-7,35] In other words, considering that DS elicits a dose-dependent response, excessive DS performance may induce muscle fatigue.[35] Therefore, an appropriate balance between muscle fatigue due to long duration or high volume and the positive effect of DS may be an important factor for eliciting a positive effect on muscle function. Additionally, in DS-AMSS and DS-RPM, other activities were performed for 5 minutes after DS, whereas in DS, the test was performed immediately after DS. Thus, the time between stretching and testing may have affected changes in muscle function.[35,36]

The three warm-up protocols did not affect explosive strength (RTD and RVD) or isokinetic muscle function. This appears to be the result of offsetting the positive (increased nerve activation and temperature) and negative (MTU stiffness reduction and muscle fatigue) effects that may occur with DS. The ability to rapidly contract muscles has been reported to be influenced by structural factors including muscle fiber type, muscle cross-sectional area, maximal muscle strength, and visco-elastic properties of the muscle-tendon complex.[13,37] Fast muscle fiber (type II) recruitment plays an important role in fast muscle contraction.[38] However, these muscle fibers are characterized by low resistance to fatigue.[39] In other words, it is considered that the muscle fatigue caused by the high dose of DS used in this study had a more negative effect on the faster angular velocity movement and explosive strength than the isometric contraction. Moreover, similar to SS, DS contributes to MTU stiffness reduction.[7] Effective force transmission to the bone by stiffness of the tendinous structures is positively associated with high-force isometric and dynamic muscle activity.[40] As mentioned earlier, a decrease in the MTU stiffness results in a decrease in the muscle force transmitted to the skeleton.[7,33] Considering the results of studies suggesting that explosive strength decreases with MTU stiffness reduction, DS may harm explosive strength. Therefore, the question remains whether a warm-up protocol involving DS (especially high dose) may improve fast angular velocity movement or explosive strength. Finally, DS consists of components of muscle stretch, muscle contractions, and passive cyclic movements.[25] Which of these components has a greater contribution to muscle function should be determined by further study.

This study has several limitations. First, different sexes may have different muscle properties, but this was not considered. Second, the long-term effects of the three warm-up protocols have not been confirmed. Third, there was a lack of a control group (no stretching or 5 minutes of rest after DS) for the three warm-up protocols.

In conclusion, although DS-AMSS and DS-RPM improve isometric PT (static contraction), the three warm-up protocols (DS, DS-AMSS, DS-RPM) do not appear to influence explosive strength and isokinetic strength (dynamic contraction) at fast angular velocity. Considering the relatively high volume of DS used in this study, this may be due to the influence of muscle fatigue. Unfortunately, the effects of different DS doses were not compared in this study. Therefore, further study is needed to determine the optimal dosage of warm-up protocols including DS to improve explosive strength. Nevertheless, the findings of this study suggest that tailored warm-up protocols for fast muscle contraction and joint acceleration, unlike isometric PT corresponding to static contraction, may require a different approach from existing methods. Increased knowledge of interventions to increase explosive strength is expected to provide scientists, including conditioning researchers and coaches, with insights for developing training and rehabilitation programs.

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