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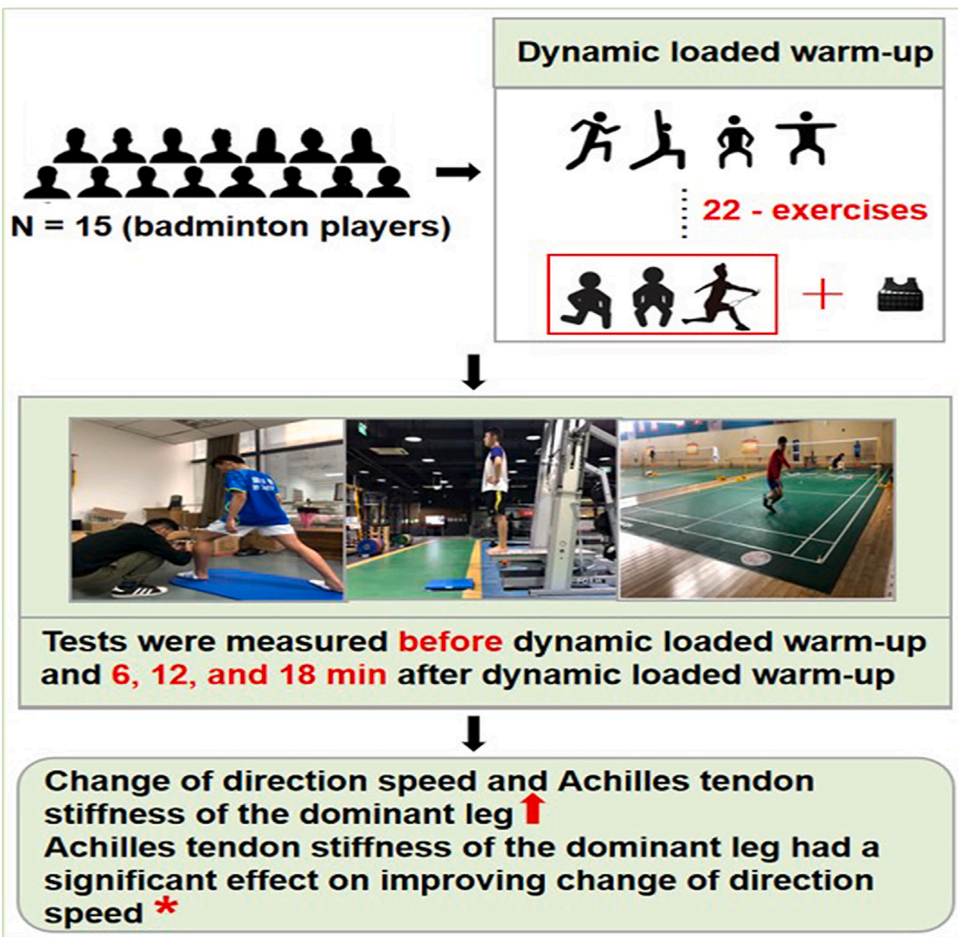

Zhihai Wang, Mingming Yang, Kaiyuan Qu, ..., Yi Sheng, Daniel T.P. Fong, Dan Wang

wangdan@sus.edu.cn

Highlights

CODS improvement in athletes lasted up to 18 min after dynamic loaded warm-up

CODS improvement is potentially related to increased AT stiffness of the dominant leg

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Does lower extremity stiffness influence change of direction speed in badminton athletes after dynamic loaded warm-up?

Zhihai Wang,[1] Mingming Yang,[1] Kaiyuan Qu,[1] Xinyu Mao,[1] Anqi Lu,[1] Yi Sheng,[1] Daniel T.P. Fong,[2] and Dan Wang[1,3,*]

SUMMARY

This study investigated whether lower extremity stiffness plays a role in the enhancement of change of direction speed (CODS) and the duration of this enhancement after dynamic loaded warm-up (DLWU). Fifteen badminton athletes underwent DLWU, and CODS, individual muscle and tendon stiffness, and vertical stiffness were measured before DLWU and 6, 12, and 18 min after DLWU. The data were analyzed using ANOVA and covariance analysis. Significant improvements in CODS were found at 6, 12, and 18 min post-DLWU compared to pre-DLWU ($p < 0.05$). The Achilles tendon stiffness of the dominant leg increased at 6 min ($p = 0.039$) and 18 min ($p = 0.024$) post-DLWU compared to pre-DLWU. Achilles tendon stiffness of the dominant leg had a significant effect on improving CODS ($p > 0.05$). CODS improvement lasted up to 18 min after DLWU in badminton athletes, potentially related to increased Achilles tendon stiffness of the dominant leg.

INTRODUCTION

Pre-exercise warm-up activities help athletes achieve optimal athletic performance.[1] Warm-up exercises have been shown to significantly improve players' strength,[2] speed,[3] and agility performance.[4] Badminton is the fastest racket sport in the world, as athletes need to hit the shuttlecock every 2 s,[5] and the average speed of the shuttlecock is up to 180–252 km/h.[6] This requires that athletes have adequate change of direction speed (CODS) to perform high-quality offensive and defensive movements by changing direction quickly and repeatedly in a small court (about 35 m^2). CODS is not only a key factor in predicting the performance of badminton players ($r = 0.74$),[7] but it also significantly correlates with the winning rate ($r = -0.83$).[8] Therefore, badminton athletes should maximize their CODS during the warm-up period, which will help them to play better in competitions.

The dynamic loaded warm-up (DLWU) exercise has recently been reported to significantly improve badminton athletes' CODS.[9] Maloney et al.[9] reported that when badminton athletes warmed up with a loaded vest of 10% of their body mass, their CODS significantly improved 6 min (tested at 15 s and 2, 4, and 6 min) after the warm-up. Nava et al.[10] reported that DLWU improved the CODS of college athletes (tennis, volleyball, and soccer sports). However, they found that the CODS of college athletes decreased at the 10- and 18-min time points compared with 2 min after the warm-up. Moreover, research has suggested that resting for more than 15–20 min after warming up may lower performance to baseline levels.[11] Furthermore, wearing a weighted vest during warm-up exercises can lead to post-activation potentiation (PAP),[9,10,12] a phenomenon that enhances neuromuscular function and improves explosive force production.[13] The PAP effect is generally attributed to the phosphorylation of myosin regulatory light chains,[14] an increase in the pinna angle,[15] and the recruitment of fast twitch muscle motor units.[16] DLWU may create a favorable environment for speed and power performance by increasing the rate of force development. Therefore, the duration of the warm-up effect may be closely related to the CODS of athletes in subsequent competition, and exploring CODS enhancement and the duration following DLWU in badminton athletes may yield valuable insights.

Stiffness describes the deformation of an object under a given force in physics.[17] In the human body, stiffness can be described from the level of a single muscle fiber to the entire body, which has been modeled as mass and spring.[18] Common measurements of stiffness in the active population include muscle stiffness, tendon stiffness, and vertical stiffness (K_{vert}).[19,20] The stiffness of the muscles and tendons is typically measured using handheld dynamometers (MyotonPRO, Myoton AS, Tallinn, Estonia). K_{vert} is often calculated by dividing the peak vertical ground reaction force in contact with the ground by the displacement of the body's center of mass.[21] Acute changes in lower extremity stiffness may be expected to increase the rate of stretch-shortening cycle (SSC) strength development during change of direction and, thus,

[1]School of Athletic Performance, Shanghai University of Sport, Shanghai, China
[2]National Centre for Sport and Exercise Medicine, School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK
[3]Lead contact
*Correspondence: wangdan@sus.edu.cn
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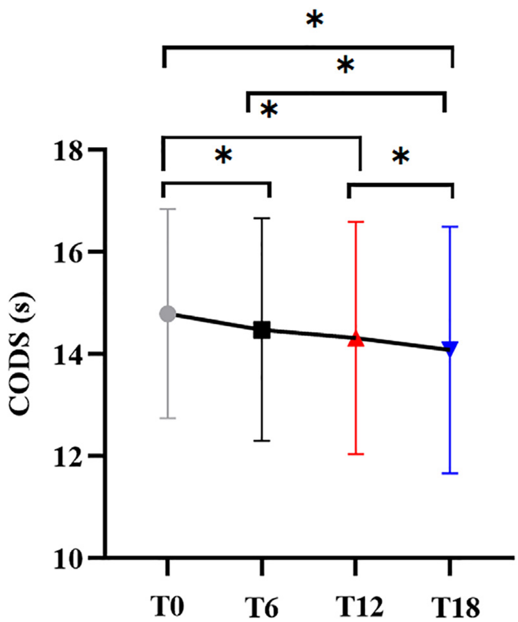

Figure 1. Effect of DLWU on athletes' CODS performance

CODS, change of direction speed; T0, pre-DLWU; T6, 6 min post-DLWU; T12, 12 min post-DLWU; T18, 18 min post-DLWU. Data are presented as means ± SD. * The main effect of time was statistically significant ($p < 0.05$).

overall CODS.[19,20] A certain level of lower extremity stiffness is essential for effectively storing and reusing elastic energy during SSC activities. An athlete with greater stiffness characteristics can store more elastic energy during the yielding phase of ground contact and generate more concentric force output at push-off, which increases running speed and CODS.[17] Improved performance in CODS has been closely linked to shorter ground contact times. Greater stiffness would likely facilitate efficient transmission of the generated impulse and minimize the required ground contact time for executing direction changes.[22] However, no studies have directly investigated whether stiffness plays a role in the enhancement of CODS after DLWU.

Thus, this study aimed to investigate the duration of the improvement in CODS in badminton athletes after DLWU and whether its improvement was due to an acute increase in lower extremity stiffness to a certain extent. We hypothesized that the athletes' improvement in CODS after DLWU would last up to 15–20 min, and that the improvement in CODS might be explained by an acute improvement in lower extremity stiffness to some extent.

RESULTS

Effect of DLWU on athletes' CODS

Figure 1 shows the changes in CODS among the badminton athletes before DLWU (T0) through 18 min (T18) after DLWU (T0–T18). The CODS of the athletes significantly improved at different time points following the DLWU ($F = 13.948$, $p < 0.001$, $\eta^2_p = 0.499$). Compared with T0, the CODS at T6 was faster by 0.31 s ($p = 0.018$), the CODS at T12 was faster by 0.48 s ($p = 0.010$), and the CODS at T18 was faster by 0.71 s ($p = 0.004$). Compared with T6, the CODS at T18 was faster by 0.40 s ($p = 0.024$). Compared with T12, the CODS at T18 was faster by 0.23 s ($p = 0.038$).

Effect of DLWU on athletes' lower extremity stiffness

Figure 2 shows the changes in the Achilles tendon (AT) stiffness of the dominant leg of the badminton athletes from T0 to T18. The AT stiffness of the dominant leg in athletes significantly increased after DLWU ($F = 3.103$, $p = 0.046$, $\eta^2_p = 0.181$). The AT stiffness of the dominant leg at T18 increased by 80.8 N/m when compared with the values at T0 ($p = 0.024$). Compared with T6, the AT stiffness of the dominant leg at T18 increased by 83.7 N/m ($p = 0.039$) (Figure 1). Furthermore, no significant changes were observed after DLWU in the following measurements: the medial gastrocnemius (MG) stiffness of the non-dominant ($p = 0.519$) and dominant ($p = 0.201$) legs, the soleus (SOL) stiffness of the non-dominant ($p = 0.536$) and dominant ($p = 0.878$) legs, the rectus femoris (RF) stiffness of the non-dominant ($p = 0.916$) and dominant ($p = 0.167$) legs, the AT stiffness of the dominant leg ($p = 0.579$), the patellar tendon (PT) stiffness of the non-dominant ($p = 0.795$) and dominant ($p = 0.386$) legs, the K_{vert} stiffness ($p = 0.747$), and the K_{vert} of the dominant ($p = 0.842$) and non-dominant ($p = 0.376$) legs.

Effect of AT stiffness on athletes' CODS

A two-way covariance analysis was conducted with CODS as the dependent variable and the change in AT stiffness of the dominant leg as the covariate. The results showed that AT stiffness of the dominant leg had a significant effect on improving CODS from T0 to T18 ($F = 0.06$, $p = 0.938$, $\eta^2_p = 0.000$) and from T6 to T18 ($F = 0.69$, $p = 0.797$, $\eta^2_p = 0.005$).

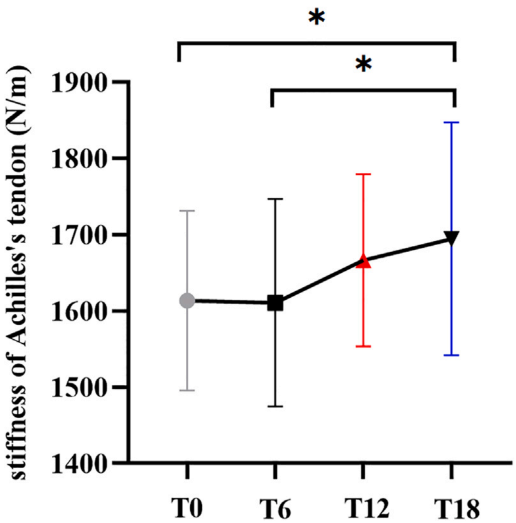

Figure 2. Effect of DLWU on athletes' stiffness of the dominant leg Achilles tendon

T0, pre-DLWU; T6, 6 min post-DLWU; T12, 12 min post-DLWU; T18, 18 min post-DLWU. Data are presented as means ± SD. * The main effect of time was statistically significant ($p < 0.05$).

DISCUSSION

The main finding of this study was that the enhancement of CODS performance in badminton athletes can last up to 18 min after the DLWU. Notably, this phenomenon might be explained by the increased AT stiffness of the dominant leg after the DLWU.

The CODS at T6, T12, and T18 of the badminton athletes was significantly improved after the DLWU compared with values at T0. The improvement in the athletes' CODS may be attributed to the PAP effect induced by the DLWU. Most scholars attribute the PAP effect to the phosphorylation of myosin regulatory light chains,[14] an increase in the pinna angle,[15] and the recruitment of fast twitch muscle motor units.[16] The results of the present study support those of Maloney et al.[9] and Nava et al.,[10] which showed that dynamic weight vest warm-up significantly enhanced CODS in participants. However, the present study observed a DLWU lasting time (18 min) that was longer than that reported by Maloney et al.[9] (6 min) and Nava et al.[10] (2 min). The CODS of the athletes in Nava et al.'s study showed a decline at 10 min and 18 min after warm-up,[10] whereas we found that the DLWU improved the CODS of badminton athletes for up to 18 min. This provides important information for badminton athletes regarding the optimal timing for DLWU.

The results of the study showed that the AT stiffness of the dominant leg of the athletes increased significantly at T18 compared to the values at T0 and T6. AT is the longest, thickest, and strongest tendon in the human body, and it is mainly responsible for the transmission of the muscle power of the triceps surae during human exercise.[23] It is the key to the effective completion of energy storage and release of the human lower limbs during walking, running, and jumping.[24] The increased AT stiffness of athletes may be the result of the PAP effect induced by repeated SSC (e.g., sprint and jumps) during DLWU,[25] which involves many loaded jogging and jumping exercises (see Table 2). Notably, a significant increase in AT stiffness following DLWU was found only in the athletes' right leg. This may be because the athlete's right leg is the dominant leg, and during daily training and competitions, the badminton player's dominant leg is required to perform a large number of braking and deceleration movements (80–90%) and bears loads up to 50–70% of their body mass,[26] Therefore, during DLWU, the dominant leg of athletes may be more easily activated and mobilized,[27] resulting in a significant increase in AT stiffness.

However, no significant changes in the individual muscle stiffness of the athletes' lower extremities were discovered after DLWU. The main reason for this might be that the tendon is the primary regulator of the relationship between force velocity and force length, rather than the muscle.[20] Tendons are elastic tissues that shorten faster than muscles.[28] It is interesting that we observed a significant change only in AT stiffness but not in PT stiffness after the DLWU. This may be because PT acts as a force-transmitting tendon during a change of direction rather than as an elastic energy storing-releasing tendon.[29] We also found no significant changes in K_{vert} following DLWU, which is inconsistent with the results reported in previous studies. Comyns et al.[30] reported that a 10.9% increase in K_{vert} was observed in rugby players after performing single-leg jumps on a sledge at 93% one repetition maximum (1RM). Moir et al.[31] found that K_{vert} increased by 16% after three repetitions of squat jumps in 90% 1RM. Studies have mentioned that participants' K_{vert} may not change when the exercise program does not adequately stimulate the eccentric strength of the muscles.[32] Witmer et al.[32] suggested that the lack of change in K_{vert} in men and women after acute resistance exercises may be due to insufficient stimulation of the exercise activity. Comyns et al.[30] pointed out that after squats with a 93% 1RM, participants' K_{vert} increased, while no difference in K_{vert} was discovered after squats with 65% and 80% 1RM. Furthermore, several factors influence lower extremity K_{vert}, such as gender and individual biomechanical properties of the lower extremity (e.g., anthropometry, joint compliance, muscle mass).[33] Therefore, the load of 10% body mass in DLWU-generated stimuli may also have contributed to the non-significant change in lower extremity K_{vert} observed in our study.

The present study is the first to identify the increase in AT stiffness of the dominant leg as an important mechanism to promote the CODS of badminton athletes after DLWU. Some researchers have proposed that the enhancement of CODS of athletes may not only be affected by the physiological mechanism discussed previously but also by the acute increase in lower extremity stiffness.[9,10] However, Maloney[9] and Nava[10] did not directly evaluate changes in stiffness before and after warm-up to verify this proposition. Studies have shown that higher stiffness is beneficial for fast SSC activities and activities involving high velocity of motion.[34–36] Greater AT stiffness allows the muscles to work in a more optimal force-velocity range.[20] Therefore, it can be expected that the increase in stiffness accelerates the rate of force development and thus contributes to the improvement of CODS.

Furthermore, increased stiffness creates more potential energy stored in the tendons, reducing muscle activity and energy expenditure at a given speed.[37] The explosive performance of athletes requires AT to provide elastic energy, and AT achieves explosive movement (such as acceleration and deceleration in change of direction) by storing and releasing elastic energy.[38] A lower limb with greater stiffness gives the athlete better resistance to deformation when in contact with the ground, thus allowing for the impulses required for change of direction to be applied in a shorter time.[17] The change of direction involves many jumps and split steps, and the increase in the athlete's AT stiffness can improve the pre-stretch efficiency of SSC to enhance the ability of rapid change of direction.[39] Furthermore, Pożarowszczyk et al.[25] found that when the AT stiffness of basketball players increased, they required less force to activate and control their muscles. This is because higher AT stiffness means that muscles can resist external forces more effectively, thereby reducing energy expenditure. This information could be important for badminton coaches and sports scientists, and more related research is needed on other types of sports and athletes in the future.

Limitations of the study

There are certain limitations to this study. As the participants of this study were college athletes, the applicability of the findings to professional athletes remains to be explored. Furthermore, given that fatigue generated by repeated testing of athletes may affect the accuracy of the results of the relevant variables, this study observed only changes in stiffness and CODS of the athletes from 6 to 18 min after DLWU.

Conclusion

To the authors' knowledge, this is the first study to explore changes in lower extremity stiffness after DLWU in badminton athletes, and the results may provide coaches and athletes with useful information in warm-up training. The study discovered that CODS improvement lasted up to 18 min after DLWU in badminton athletes. Badminton strength and conditioning coaches can consider incorporating the DLWU program into athletes' overall warm-up programs before the competition. Moreover, this is the first study showing that the increase in AT stiffness of the dominant leg after DLWU of badminton athletes may be one of the macro mechanisms leading to the improvement of CODS performance. Since stiffness is a modifiable neuromechanical property, acute or long-term training programs to enhance AT stiffness may positively affect badminton athletes' CODS.

Practical applications

The findings present the DLWU as a practical program that can significantly improve and sustain the CODS of badminton athletes for up to 18 min. The potential for longer-lasting effects remains a subject for future research. Moreover, the increased AT stiffness of the dominant leg may occur through further improvement in the athlete's CODS by enhancing the storage and release of elastic energy and saving energy consumption.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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AUTHOR CONTRIBUTIONS

Conceptualization, Z.H.W. and D.W.; investigation, Z.H.W., M.M.Y., K.Y.Q., X.Y.M., A.Q.L., and Y.S.; data analysis, Z.H.W. and D.W.; writing – original draft, Z.H.W. and D.W.; writing – review & editing, Z.H.W., D.T.P.F., and D.W.

DECLARATION OF INTERESTS

No potential conflict of interest was reported by the authors.

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REFERENCES

1. McGowan, C.J., Pyne, D.B., Thompson, K.G., and Rattray, B. (2015). Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications. Sports Med. *45*, 1523–1546. https://doi.org/10.1007/s40279-015-0376-x.
2. Chen, C.H., Chiu, C.H., Tseng, W.C., Wu, C.Y., Su, H.H., Chang, C.K., and Ye, X. (2023). Acute Effects of Combining Dynamic Stretching and Vibration Foam Rolling Warm-up on Lower-Limb Muscle Performance and Functions in Female Handball Players. J. Strength Cond. Res. *37*, 1277–1283. https://doi.org/10.1519/jsc.0000000000003998.
3. Williams, J.J., Herron, R.L., Spradley, B., and Saracino, P. (2021). Postactivation Potentiation Effect of Heavy Sled Towing on Subsequent Sprints. J. Strength Cond. Res. *35*, 1229–1233. https://doi.org/10.1519/jsc.0000000000003863.
4. Chua, M.T., Chow, K.M., Lum, D., Tay, A.W.H., Goh, W.X., Ihsan, M., and Aziz, A.R. (2021). Effectiveness of On-Court Resistive Warm-Ups on Change of Direction Speed and Smash Velocity during a Simulated Badminton Match Play in Well-Trained Players. J. Funct. Morphol. Kinesiol. *6*, 81. https://doi.org/10.3390/jfmk6040081.
5. Faude, O., Meyer, T., Rosenberger, F., Fries, M., Huber, G., and Kindermann, W. (2007). Physiological characteristics of badminton match play. Eur. J. Appl. Physiol. *100*, 479–485. https://doi.org/10.1007/s00421-007-0441-8.
6. Gowitzke, B.A. (1979). Technique of badminton stroke production (Science in Racquet Sports), pp. 17–41.
7. Hughes, M.G., and Cosgrove, M. (2006). Badminton. In Sport and Exercise Physiology Testing Guidelines: Volume I-Sport Testing (Routledge), pp. 234–239.
8. Tiwari, L., Rai, V., and Srinet, S. (2011). Relationship of selected motor fitness components with the performance of badminton player. Asian J Phys Educ Comput Sci Sports *5*, 88–91.
9. Maloney, S.J., Turner, A.N., and Miller, S. (2014). Acute Effects of a Loaded Warm-Up Protocol on Change of Direction Speed in Professional Badminton Players. J. Appl. Biomech. *30*, 637–642. https://doi.org/10.1123/jab.2014-0048.
10. Nava, K.M. (2015). The Acute Effects of Different Warm-Up Techniques of Power Output (University of Texas Rio Grande Valley).
11. Silva, L.M., Neiva, H.P., Marques, M.C., Izquierdo, M., and Marinho, D.A. (2018). Effects of Warm-Up, Post-Warm-Up, and Re-Warm-Up Strategies on Explosive Efforts in Team Sports: A Systematic Review. Sports Med. *48*, 2285–2299. https://doi.org/10.1007/s40279-018-0958-5.
12. Thompsen, A.G., Kackley, T., Palumbo, M.A., and Faigenbaum, A.D. (2007). Acute effects of different warm-up protocols with and without a weighted vest on jumping performance in athletic women. J. Strength Cond. Res. *21*, 52–56. https://doi.org/10.1519/00124278-200702000-00010.
13. Sale, D.G. (2002). Postactivation potentiation: role in human performance. Exerc. Sport Sci. Rev. *30*, 138–143. https://doi.org/10.1097/00003677-200207000-00008.
14. Sweeney, H.L., Bowman, B.F., and Stull, J.T. (1993). Myosin light chain phosphorylation in vertebrate striated muscle: regulation and function. Am. J. Physiol. *264*, C1085–C1095. https://doi.org/10.1152/ajpcell.1993.264.5.C1085.
15. Mahlfeld, K., Franke, J., and Awiszus, F. (2004). Postcontraction changes of muscle architecture in human quadriceps muscle. Muscle Nerve *29*, 597–600. https://doi.org/10.1002/mus.20021.
16. Güllich, A., and Schmidtbleicher, D. (1996). MVC-induced short-term potentiation of explosive force. New studies in athletics *11*, 67–84.
17. Brazier, J., Maloney, S., Bishop, C., Read, P.J., and Turner, A.N. (2019). Lower extremity stiffness: considerations for testing, performance enhancement, and injury risk. J. Strength Cond. Res. *33*, 1156–1166. https://doi.org/10.1519/JSC.0000000000002283.
18. Butler, R.J., Crowell, H.P., 3rd, and Davis, I.M. (2003). Lower extremity stiffness: implications for performance and injury. Clin. Biomech. *18*, 511–517. https://doi.org/10.1016/s0268-0033(03)00071-8.
19. Pruyn, E.C., Watsford, M., and Murphy, A. (2014). The relationship between lower-body stiffness and dynamic performance. Appl Physiol Nutr Metab *39*, 1144–1150. https://doi.org/10.1139/apnm-2014-0063.
20. Kalkhoven, J.T., and Watsford, M.L. (2018). The relationship between mechanical stiffness and athletic performance markers in sub-elite footballers. J. Sports Sci. *36*, 1022–1029. https://doi.org/10.1080/02640414.2017.1349921.
21. McMahon, T.A., and Cheng, G.C. (1990). The mechanics of running: how does stiffness couple with speed? J. Biomech. *23*, 65–78.
22. Bret, C., Rahmani, A., Dufour, A.-B., Messonnier, L., and Lacour, J.R. (2002). Leg strength and stiffness as ability factors in 100 m sprint running. J. Sports Med. Phys. Fitness *42*, 274–281.
23. Doral, M.N., Alam, M., Bozkurt, M., Turhan, E., Atay, O.A., Dönmez, G., and Maffulli, N. (2010). Functional anatomy of the Achilles tendon. Knee Surg. Sports Traumatol. Arthrosc. *18*, 638–643. https://doi.org/10.1007/s00167-010-1083-7.
24. Bohm, S., Mersmann, F., and Arampatzis, A. (2015). Human tendon adaptation in response to mechanical loading: a systematic review and meta-analysis of exercise intervention studies on healthy adults. Sports Med. Open *1*, 7. https://doi.org/10.1186/s40798-015-0009-9.
25. Pożarowszczyk, B., Gołaś, A., Chen, A., Zając, A., and Kawczyński, A. (2018). The Impact of Post Activation Potentiation on Achilles Tendon Stiffness, Elasticity and Thickness among Basketball Players. Sports (Basel) *6*, 117. https://doi.org/10.3390/sports6040117.
26. Omosegaard, B., and Tindholdt, L. (1996). Physical Training for Badminton (International Badminton Federation).
27. Jeffreys, I., and Moody, J. (2021). Strength and Conditioning for Sports Performance (Routledge).
28. Cardinale, M., Newton, R., and Nosaka, K. (2011). The Stretch Shortening Cycle (SSC) (Wiley-Blackwell).
29. Cristi-Sánchez, I., Danes-Daetz, C., Neira, A., Ferrada, W., Yáñez Díaz, R., and Silvestre Aguirre, R. (2019). Patellar and Achilles Tendon Stiffness in Elite Soccer Players Assessed Using Myotonometric Measurements. Sports Health *11*, 157–162. https://doi.org/10.1177/1941738118820517.
30. Comyns, T.M., Harrison, A.J., Hennessy, L., and Jensen, R.L. (2007). Identifying the optimal resistive load for complex training in male rugby players. Sports BioMech. *6*, 59–70. https://doi.org/10.1080/14763140601058540.

31. Moir, G.L., Mergy, D., Witmer, C., and Davis, S.E. (2011). The acute effects of manipulating volume and load of back squats on countermovement vertical jump performance. J. Strength Cond. Res. *25*, 1486–1491. https://doi.org/10.1519/JSC.0b013e3181da8597.
32. Witmer, C.A., Davis, S.E., and Moir, G.L. (2010). The acute effects of back squats on vertical jump performance in men and women. J. Sports Sci. Med. *9*, 206–213.
33. Colson, S.S., and Petit, P.D. (2013). Lower limbs power and stiffness after whole-body vibration. Int. J. Sports Med. *34*, 318–323. https://doi.org/10.1055/s-0032-1311596.
34. Chelly, S.M., and Denis, C. (2001). Leg power and hopping stiffness: relationship with sprint running performance. Med. Sci. Sports Exerc. *33*, 326–333. https://doi.org/10.1097/00005768-200102000-00024.
35. Brughelli, M., and Cronin, J. (2008). A review of research on the mechanical stiffness in running and jumping: methodology and implications. Scand J Med Sci Spor *18*, 417–426. https://doi.org/10.1111/j.1600-0838.2008.00769.x.
36. Arampatzis, A., Schade, F., Walsh, M., and Brüggemann, G.P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. J. Electromyogr. Kinesiol. *11*, 355–364. https://doi.org/10.1016/s1050-6411(01)00009-8.
37. Barnes, K.R., Hopkins, W.G., McGuigan, M.R., and Kilding, A.E. (2015). Warm-up with a weighted vest improves running performance via leg stiffness and running economy. J. Sci. Med. Sport *18*, 103–108. https://doi.org/10.1016/j.jsams.2013.12.005.
38. Park, D.Y., and Chou, L. (2006). Stretching for prevention of Achilles tendon injuries: a review of the literature. Foot Ankle Int. *27*, 1086–1095. https://doi.org/10.1177/107110070602701215.
39. Phomsoupha, M., and Laffaye, G. (2020). Multiple Repeated-Sprint Ability Test With Four Changes of Direction for Badminton Players (Part 2): Predicting Skill Level With Anthropometry, Strength, Shuttlecock, and Displacement Velocity. J. Strength Cond. Res. *34*, 203–211. https://doi.org/10.1519/JSC.0000000000002397.
40. Valldecabres, R., Richards, J., and De Benito, A.M. (2022). The effect of match fatigue in elite badminton players using plantar pressure measurements and the implications to injury mechanisms. Sports BioMech. *21*, 940–957. https://doi.org/10.1080/14763141.2020.1712469.
41. Brophy, R., Silvers, H.J., Gonzales, T., and Mandelbaum, B.R. (2010). Gender influences: the role of leg dominance in ACL injury among soccer players. Br. J. Sports Med. *44*, 694–697. https://doi.org/10.1136/bjsm.2008.051243.
42. Yeung, W.C.V., Bishop, C., Turner, A.N., and Maloney, S.J. (2021). Does a Loaded Warm-Up Influence Jump Asymmetry and Badminton-Specific Change of Direction Performance? Int. J. Sports Physiol. Perform. *16*, 578–584. https://doi.org/10.1123/ijspp.2020-0313.
43. Faigenbaum, A.D., McFarland, J.E., Schwerdtman, J.A., Ratamess, N.A., Kang, J., and Hoffman, J.R. (2006). Dynamic warm-up protocols, with and without a weighted vest, and fitness performance in high school female athletes. J. Athl. Train. *41*, 357–363.
44. Freriks, B., Hermens, H., Disselhorst-Klug, C., and Rau, G. (1999). The recommendations for sensors and sensor placement procedures for surface electromyography. Seniam *8*, 13–54.
45. Ditroilo, M., Hunter, A.M., Haslam, S., and De Vito, G. (2011). The effectiveness of two novel techniques in establishing the mechanical and contractile responses of biceps femoris. Physiol. Meas. *32*, 1315–1326. https://doi.org/10.1088/0967-3334/32/8/020.
46. Peng, H.T. (2011). Changes in biomechanical properties during drop jumps of incremental height. J. Strength Cond. Res. *25*, 2510–2518. https://doi.org/10.1519/JSC.0b013e318201bcb3.
47. Maloney, S.J. (2016). The Relationship between Stiffness, Asymmetries and Change of Direction Speed (University of Bedfordshire).

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
G*Power 3.1.9.2	Franz-Faul, Universität Kiel, Germany	https://stats.oarc.ucla.edu/other/gpower/
SPSS software version 22.0	SPSS software version 22.0	N/A
GraphPad Prism 8	GraphPad Software	https://www.graphpad.com/
Other		
Loaded vest	PROIRON, Shanghai, China	N/A
MyotonPRO	MyotonPRO, Myoton AS, Tallinn, Estonia	https://www.myoton.com/technology/
Stopwatch	Fuhai Chemical Glass Instrument Co., Ltd., Shenzhen, China	N/A
Force plate (Kistler)	Kistler Instruments, Winterthur, Switzerland	N/A

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resource could be direct to the lead contact Dan Wang (wangdan@sus.edu.cn).

Materials availability

The study did not generate new unique reagents.

Data and code availability

- This study did not generate original code.
- Any additional information required to reanalyse the data reported in this paper is available from the lead contact upon request.
- All data produced in this study are included in the published article and its supplemental information, or are available from the lead contact upon request.

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Participants recruitment

A total of 15 adolescent badminton athletes (9 males: 19.8 ± 2.5 years, and 6 females: 20.2 ± 1.2 years; see below table) were recruited for the study. The minimal sample size of 4 was calculated using a sample size calculator (G*Power 3.1.9.2, Franz-Faul, Universität Kiel, Germany) with an effect size of 0.83 (based on parameters of CODS[9]), α of 0.05, and power of 0.80. Participants were located in the country where the study was conducted: China. The athlete's racket hand and dominant leg were all right side (the athlete's preferred racket-holding hand was designated as the dominant side[40,41]). The inclusion criteria were as follows: (1) national excellent and first-class athletes who had participated in provincial and national level badminton competitions, (2) no severe knee, ankle, and hip injuries or surgery within the last 3 months, and (3) regular badminton training for at least 4 years[42] To reduce the learning effect of the testing process, all athletes needed to be familiar with the entire testing process in advance to ensure that they were proficient in completing all tests. No strenuous exercise, alcohol consumption, or caffeine intake the day before the test. All athletes who participated in the study signed an informed consent form. The study was approved by the Human Research Ethics Committee of Shanghai University of Sport (NO.102772020RT100).

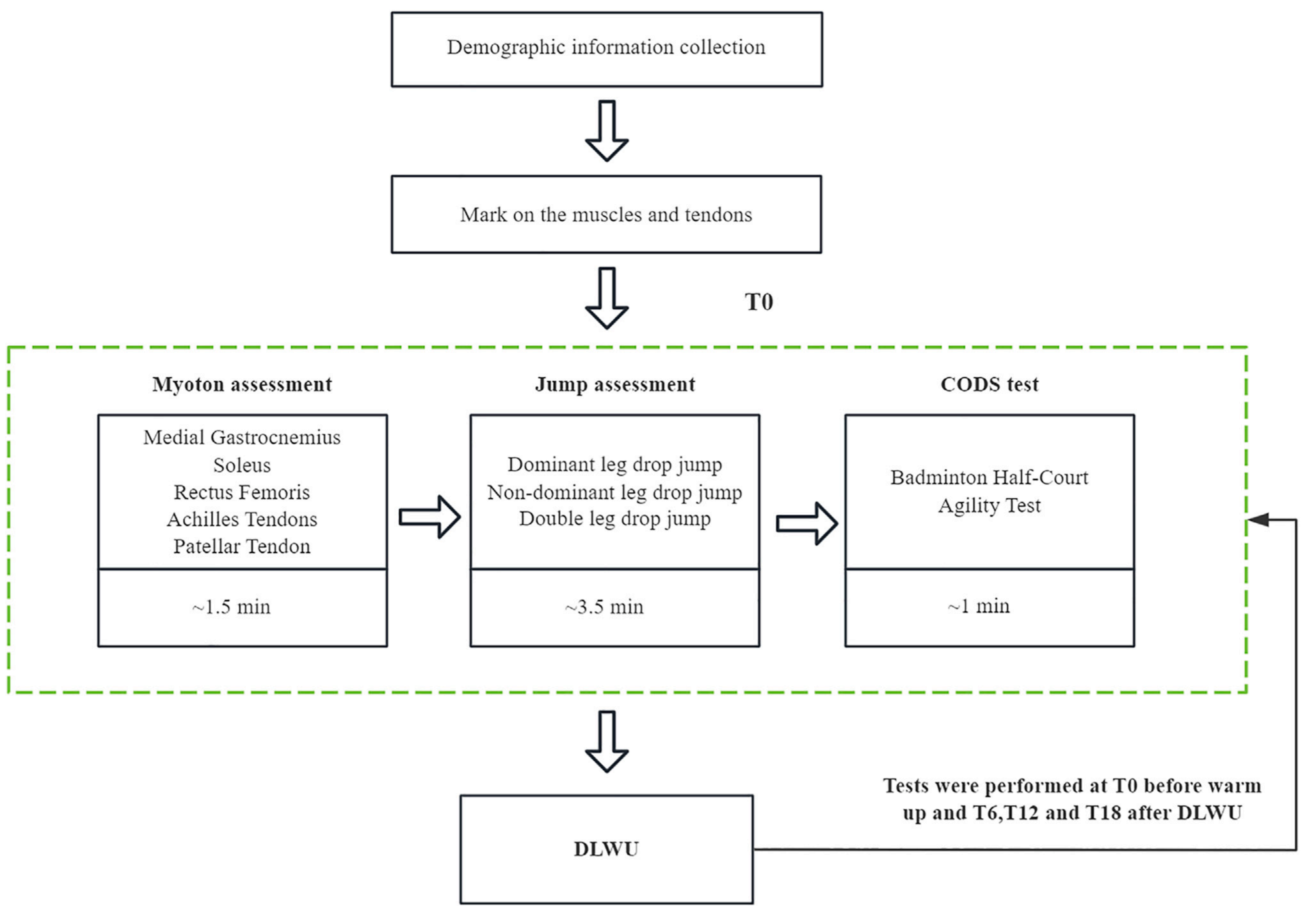
Demographic information of badminton athletes (mean ± SD)

	N	Height (m)	Body mass (kg)	Age (years)	Training experience (years)
Males	9	1.80 ± 0.07	71.0 ± 9.9	19.8 ± 2.5	10.9 ± 1.5
Females	6	1.69 ± 0.07	60.0 ± 7.5	20.2 ± 1.2	13.0 ± 1.4

METHOD DETAILS

Experimental procedure

All training and testing were conducted at the badminton court of Shanghai University of Sports, and the researchers were trained to be proficient in the entire testing process. The flowchart of this study is shown in below figure. Before DLWU (T0), the muscle and tendon sites were marked for stiffness measurement. The stiffness of individual muscles and tendons in the natural standing position was measured using MyotonPRO (MyotonPRO, Myoton AS, Tallinn, Estonia) (see below figure). The athletes then performed three drop jump tests (including the non-dominant leg, dominant leg, and double legs) with a 1-min rest interval to avoid fatigue occurrence. Lastly, the badminton half-court agility test was conducted on the badminton court. The athletes repeated the T0 testing procedure at T6, T12, and T18 following DLWU (See below table).



The flowchart of the study

CODS, change of direction speed; DLWU, dynamic loaded warm-up; T0, pre-DLWU; T6, 6 min post-DLWU; T12, 12 min post-DLWU; T18, 18 min post-DLWU.

MyotonPRO

The dynamic loaded warm-up program	
Warm-up drills	
Dynamic flexibility	
1	Walking on toes
2	Walking on heels
3	Walking knee to chest
4	Walking knee to chest with internal rotation
5	Walking hip circles—medial to lateral
6	Walking hip circles—lateral to medial
7	Walking lunge & rotate
8	Walking deep lunge
9	Walking sumo squats
Pulse raiser	
10	Jogging with high knees
11	Jogging with butt kicks
12	Fast feet running
13, 14, 15	Repeat 10, 11, 12 backward
16, 17	Side steps × 2—alternate lead foot
18, 19	Carioca steps × 2—alternate lead foot
Speed & power drills	
20[a]	Bilateral countermovement jumps (×5 repetitions)
21[a]	Alternating split squat jumps (×5 repetitions each leg)
22[a]	4-corners shadow play drill (×2 circuits)

[a]The athletes were required to wear load vests to complete the warm-up exercise.

DLWU procedure

The DLWU routines are shown in Table 2.[9] On a badminton court, 18.3 m in length was measured, and then a marker cone was placed every 6.1 m from the starting point. The athletes jogged 6.1 m, then they started Exercise 1 in the next 6.1 m, and jogged the rest 6.1 m. Thereafter, the athletes completed the rest of the warm-up exercises (2–19) consecutively. Exercises 20–22 were performed in the badminton half-court with a loaded vest (Load Vest, PROIRON, Shanghai, China) (See below figure).[43] The vest load was 10% of the athlete's body mass.[9] Sixty-second intervals were in between among Exercises 20, 21, and 22.

Weight vest

Individual muscle and tendon stiffness

Individual muscle and tendon stiffness were measured using a handheld myometer. MyotonPRO has been widely used for stiffness measurement in field testing.[19,20] To ensure that the measurement sites were consistent before and after the DLWU, markers were made on five testing sites on dominant and non-dominant legs according to SENIAM guidelines[44]: MG, SOL, RF, AT, and PT. The athletes were instructed to stand barefoot and relax while the myometer probe was vertically placed on each muscle and tendon. The resultant impact (duration: 15 ms; force: 0.58 N) caused a temporary deformation of the tissue. The damped natural oscillations caused by the probe impact were measured using accelerometers within the device, which were sampled at a rate of 3200 Hz.[45] The mean stiffness values of the five measurements were used for further analysis.

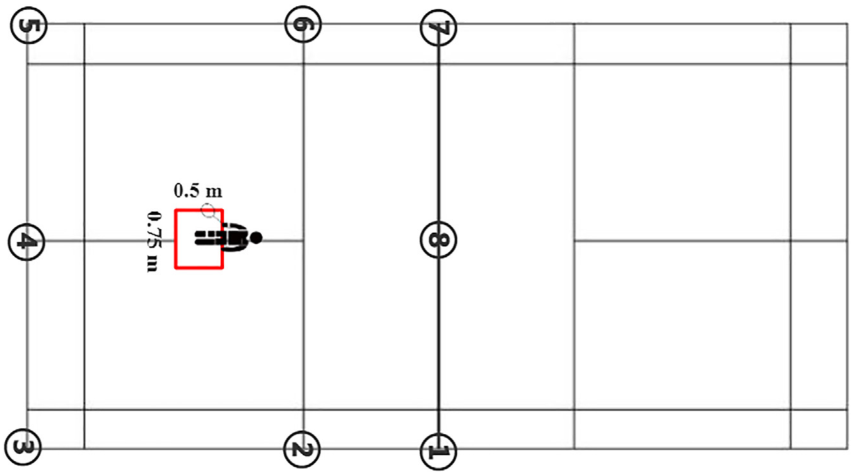
Vertical stiffness

K_{vert} was assessed for both legs using a bilateral drop jump test on a force plate (Kistler, Kistler Instruments, Winterthur, Switzerland), and K_{vert} was measured for dominant and non-dominant legs using a unilateral drop jump test. Athletes were instructed to perform single- and double-leg drop jumps to help them become familiar with the testing procedure. The athletes were then asked to stand barefoot on the box (double-leg drop jump height: 40 cm; single-leg drop jump height: 18 cm) with their hands on their hips. Previous studies have found that when the height of the drop jump exceeds 40 cm, the mechanical efficiency (SSC power output) and stiffness of the lower extremity begin to gradually decrease.[46] Furthermore, when athletes choose higher single-leg drop jump heights (such as 30 or 45 cm), they are unable to effectively reduce the time spent in contact with the ground during jumping.[47] Maloney et al. used a single-leg drop jump task (18 cm) to assess the asymmetry of K_{vert} among college students.[47] At the command given by the tester, the athlete dropped (not jumped) from the box and immediately performed a maximum effort vertical jump when landing on the ground. In this study, the athletes were required to minimize ground contact time during each jump and were advised to imagine the ground as "hot coal" to motivate them to complete the push-off action as quickly as possible. Each athlete performed three drop jump tests, with a rest of 1 min in between the tests to avoid fatigue. K_{vert} data were normalized by body bass.[21] for further analysis.

CODS assessment

The badminton half-court agility test was used to assess the CODS of the athletes (shown in below figure).[9] The athletes were required to initiate their movement from a rectangular area (0.75 m × 0.50 m) marked by red tape and to proceed in a clockwise direction to contact the shuttlecock with their racket at eight designated points. The time was recorded in seconds to two decimal places with a stopwatch (Fuhai

Chemical Glass Instrument Co., Ltd., Shenzhen, China). The reliability and validity of using a stopwatch to record time have been previously established.[9,42]



Badminton half-court agility test

QUANTIFICATION AND STATISTICAL ANALYSIS

IBM SPSS Statistics 22.0 (SPSS Inc., Chicago, IL, USA) was used for the data analysis. The Shapiro–Wilk method was used to test for data normality. One-way repeated measures (ANOVA) were selected to analyze the data on lower extremity muscle stiffness, tendon stiffness, K_{vert}, and CODS measured at different time points. Bonferroni was conducted for the post hoc comparison. The significance was set at $p < 0.05$. The effect of lower extremity stiffness on CODS was analyzed using covariance analysis (ANCOVA), with the change in AT stiffness as the covariate.