THE EFFECT OF LEG STIFFNESS ON REACTIVE AGILITY, JUMPING AND SPEED IN GYMNASTICS ATHLETES

Gokhan Delıceoglu[1], Guler Atalay[2] and Banu Kabak[3],

[1]Gazi University, Faculty of Sports Sciences, Department of Coaching, Türkiye.
[2]University of Health Sciences, Gulhane Vocational School of Health, Türkiye.
[3]Ministry of Youth and Sports, Center of Athlete Training and Health Research, Türkiye

Original article *DOI: 10.52165/sgj.16.1.55-65*

Abstract

In reviewing the literature, it was decided to conduct this study due to the lack of studies investigating the influence of leg stiffness on performance parameters such as reactive agility, jumping power and speed in gymnasts. The aim of this study is to investigate the effects of gymnasts' leg stiffness on performance parameters such as reactive agility, jump and speed. For this purpose, 65 gymnastics athletes aged 12-22 years were included in the study. The drop jump test (with Optojump measuring device) was used to evaluate the jump, and the vertical jump test (Optojump measuring device) for the evaluation of leg stiffness, while the 20m sprint test (with Witty measuring device) was made for speed evaluation. The measurements of reactive agility were performed with the SpeedCourt™. As a result of our study, we found a moderate positive correlation between the leg stiffness values and the reactive strength index (RSI) values obtained from the gymnastics athletes' jump tests. In addition, we found a negative relationship at a low level between speed and agility with leg stiffness values. It can be concluded that increasing gymnasts' leg stiffness contributes positively to jumping power, speed and reactive agility. In this case, it is recommended to include plyometric exercises in the training programs to improve the leg stiffness of trampoline gymnasts, rhythmic gymnasts and artistic gymnasts who focus on jumping.

Keywords: *gymnastics, jumping, leg stiffness, reactive agility, speed*

INTRODUCTION

Leg stiffness is a quantitative measure of the body's elastic properties and determines its ability to accumulate potential elastic energy (Butlar et al.,2003: 511-517; Struzik et al., 2021:1). The ability to absorb and return potential elastic energy is also observed in the muscle-tendinous groups in the human body. During the contractile cycle of a muscle, for example, during the lengthening of the entire muscle-tendon unit, the potential elastic energy stored by passive structures (tendon and aponeurosis) can increase the energy supplied by adaptive tissues during the

progressive shortening phase. Consequently, the capacity of the tendon and aponeurosis to store elastic tension energy can increase the total mechanical energy produced by the muscle-tendon unit during the concentric phase of muscle work or decrease muscle fiber work and metabolic energy expenditure. The potential elastic energy stored in the muscle-tendon units reduces the metabolic energy expended by the muscles responsible for movement in certain joints and is associated with the change in the kinetic energy of the moved body. (Struzik et al., 2021:1; Zawadzkı& Struzik, 2019:154-160). Therefore, stiffness, which is a quantitative measure of the resistance of an elastic body to deformation, can be seen as an important factor in optimizing human movement as it is related to the maximum performance of cyclic and single dynamic movements. (Butlar et al.,2003: 511-517; Dalleau et al., 2004:170-176; Maloney &Fletcher, 2021:109-130).

Gymnastics includes a range of activities ranging from slow extension-shortening cycles (ground contact time >250ms; e.g. acrobatic skills on the beam) to fast extension-shortening cycle activities (ground contact time <250 ms; e.g. rolling) (Mcneal et al.,2007:375-390). The elongation-shortening cycle performances can be evaluated by the reactive strength index (RSI) and leg stiffness in athletes (Lloyd et al., 2012: 2812-2819; Lloyd et al., 2015:1239-1247). Leg stiffness represents the average stiffness of the musculoskeletal system during ground contact (Farley et al., 1998:1044-155). The ability to generate and maintain high stiffness is an important factor of maximum performance in explosive exercises and is generally thought to affect the mechanics and kinematics of contact with the ground, where it affects muscle performance through changes in strength, power, and flexibility (Maquirriain, 2013:48-53).

Speed is defined as the ability to cover distances quickly. Speed is necessary in most sports to show a successful level of efficiency, as it allows athletes to move quickly in a straight direction (Bompa& Haff, 2015:315-320). Agility, on the other hand, can be defined as a sudden change in speed of whole-body movement or change in direction in response to a stimulus (Sheppard et al., 2006: 342-349). Agility commonly preserves motor control in either the vertical or horizontal direction. It also provides an effective combination of stopping, changing direction and acceleration (Verstegen& Marcello, 2001: 139-166). Arampatzis et al. (1999: 1349-1353), in their published study, stated that running speed was associated with leg stiffness.

While the existing literature offers insights into the connection between leg stiffness in gymnastic athletes and various performance aspects, specific studies directly examining this link remain scarce. Notably, Marina et al. (2012) employed a similar metric (albeit under a different name) to analyze jumping performance extensively. Their work identified and differentiated key components of jumping force associated with distinct gymnastic techniques, particularly in floor and vault routines. Furthermore, a longitudinal study by Marina and Jemni (2014) tracked the effectiveness of jumping training in female elite gymnasts over two competitive seasons using this same ratio. Building upon this established link, the present study aims to delve deeper by investigating the specific impact of leg stiffness on reactive agility, jump, and speed parameters in elite gymnasts.

Our study sought to find answers to the following questions:

- Does leg stiffness affect reactive agility in gymnasts?
- Does leg stiffness affect the reactive strenght index (RSI) measured in jumps in gymnastics?
- Does leg stiffness affect speed in gymnasts?

METHODS

Ethical approval for the study was obtained from Gazi University Ethics Committee (E-77082166-604.01.02-322274). Sixty-five athletes between the ages of 12-22, affiliated with the Turkish Gymnastics Federation, who have been engaged in gymnastics for at least 3 years were included in the study. Only athletes who had not competed in the past and had no lower extremity injuries in the last 6 months were included in the study. It was planned to evaluate the athletes who met the above criteria over the period of two days. After the demographic information (age, gender, height, weight, sports age) of the athletes was taken, warm-up exercises were performed for 15 minutes. The drop jump test for jump evaluation, the vertical jump test for lower extremity stiffness, and the 20m sprint test for speed evaluation were all conducted on the first day. On the second day, reactive agility measurements were made with a Speedcourt device. Athletes underwent tests ranging from easy to difficult exertion levels. Athletes first completed measurements by participating in the leg stiffness test, followed by the drop jump, and finally the 20-meter sprint test. On the first day, they concluded their initial assessments. On the second day, athletes participated in the reactive agility test. A five-minute rest period was provided between the two different tests (Bishop et al., 2011).

In this section, data collection tools, data gathering procedures, and statistical analyses are detailed.

For the leg stiffness test, athletes were asked to jump as high as possible 7 times without stopping, keeping the minimum contact time with the ground, hands at the waist, feet parallel to each other and without bending the knees. The leg stiffness test was carried out using the OPTO-Jump ® sistemi (Microgate, Bolzano, İtalya) device. 1 m Opto-Jump sticks (With a 96-diode resolution and a 1 kHz sampling rate, this enables the measurement of flight and contact times with a precision of 1/1000th of a second during the execution of a series of jumps) were placed on the ground with a maximum distance of 6 m between them. The athletes jumped between these two bars 7 times without interruption. Using the mean contact and flight times from all jumps and the participant's body mass, leg stiffness was calculated using the equation. The Leg Stiffness test involves having the athlete stand with hands on the hips, feet parallel, and knees minimally flexed in an upright position, ensuring minimal ground contact time by jumping as high as possible without leaving the ground. The measurement protocol involved initiating the jump on a signal and stopping after 10 seconds based on an alert. Athletes received a practice trial followed by two actual measurements with a 30-second rest between them.

Leg stiffness values are calculated using the formula below, utilizing the best flight and ground contact times:

$KN = M \times \pi\ (Tf + Tc) \div Tc\ 2\ [(Tf + Tc \div \pi) - (Tc \div 4)]$ (Dalleau et al.,2004).

In this case, M represents body mass, Tf is the flight time, Tc is the ground contact

time, and π is the mathematical constant pi (approximately 3.14159).

When examining the structural characteristics of the discipline, it is observed that during competitions, techniques involve explosive features, particularly encompassing jumps and descents. In this context, a test protocol incorporating the characteristic of drop jump has been considered. The evaluation involved calculating the reactive strength index (RSI) using the drop jump test (depth jump), and measurements were conducted using the Opto-jump device. Athletes performed a drop jump starting from a 20 cm frame height, and the crate height was increased until the maximum breakage point was achieved. The test for each athlete was completed by noting the height at which the breakage occurred (for safety reasons, the crate height was increased to a maximum of 60 cm, considering the participants were younger gymnasts). Gymnasts performed drop jump (DJ) performances barefoot from step heights of 20, 40, and 60 cm. Athletes demonstrated two DJ performances at each height with a 1-minute rest between measurements. The Reactive Strength Index (RSI) was calculated as the ratio of the athlete's jump height in meters to the ground contact time (Ramirez-Campillo et al., 2023; Young, 1995). The best RSI value obtained from the two measurements was used in the analyses.

Running speed was assessed utilizing the Opto-jump modular system (Microgate, Bolzano, Italy), an optical measuring device. The Optojump Modular is an optical measurement system consisting of transmitter and receiver bars, each equipped with 96 LEDs and a resolution of 1.0416 cm. LEDs on the transmitter bar maintain constant communication with those on the receiver bar. The system identifies interruptions in communication between the bars, calculates their duration, and facilitates the measurement of flight and ground contact times with a precision of 1/1000th of a second during running. The running system is achieved by using consecutive one-meter modules connected to each other. OptoJump is employed in conjunction with the Witty Timing system (Microgate, Italy). Athletes commenced from the starting line and completed the distance of 20m at the their maximum speed. The finishing time was for each athlete recorded in seconds (sec), and the finishing speed in m/sec. Each athlete's performance was measured twice with a 2-minute rest interval between them. The best measurement result obtained from these repetitions was used in the analyses.

All tests were conducted in a closed area on the SpeedCourt™ system (Globalspeed GmbH, Hemsbach, Germany). Speedcourt™ is a recently employed method designed for the development and evaluation of deflection speed and reactive agility. The Speedcourt™ has demonstrated utility, validity and reliability in detecting multidirectional deflections (Duking et al., 2016: 130-136). The Speedcourt™ comprises a TV screen, a square area (6.20 x 6.20 m) with 10 pressure sensors and a personal computer. Pressure sensors are arranged in 50 x 50 cm squares on the site. The entire area and the 10 pressure sensors are displayed on the TV screen. Each pressure sensor detects a minimum force of 150 N, and contact times are determined in milliseconds. The test begins with a countdown, and one of the square areas (pressure sensors) turns white on the screen. Athletes are required to run and touch the sensor with the white light. Participants must monitor the screen, following the

white square area both while running on the field and touching the appropriate square area. As soon as the athlete touches a square, another square sensor is illuminated in white, and the athlete must touch that square area as quickly as possible. The test is completed after 10 frames. Measurements were taken from each athlete with a 30-second rest interval between them, and the best result obtained from these measurements was used in the analyses.

Mean and standard deviation values were taken for descriptive statistics. The Kolmogorov-Smirnov test was employed for the normality analysis of the obtained data. Data demonstrating normal distribution were further examined for the relationship between predictor and response variables using regression analysis. The results of the T-test within the regression analysis were interpreted to assess the variability of variances. A regression analysis was conducted to predict the leg stiffness using the speed and reactive force index values obtained from the gymnasts. Statistical operations were carried out using the SPSS 20.0 software package. $P < 0.05$ was accepted as a significance value.

RESULTS

The regression analysis results regarding the prediction of leg stiffnes (X=17.20±6.56) values along with the intermediate values of agility and speed obtained from gymnasts are given in Table 1.

Table 1. *Regression analysis results on predicting leg stiffnes of gymnasts' agility and at different distances speed values.*

Variable	Mean	SD	B	Std Error	β	T	p	Zero-Order	Partial r
Constant			59.805	12.965		4.613	.000		
Agility	25.39	2.24	-.335	.452	-.115	-.741	.462	-.368	-,097
0-5 m	.90	.068	7.420	136.965	.078	.054	.957	-.259	,007
5-10 m	.78	.055	-1.220	138.183	-.010	-.009	.993	-.343	-,001
0-10 m	1.69	.11	-5.507	136.885	-.094	-.040	.968	-.327	-,005
10-20 m	1.40	.12	6.202	15.919	.120	.390	.698	-.332	,051
0-20 m	3.10	.23	-12.615	6.845	-.455	-1.843	.070	-.461	-,235
R=.476			R^2=.226						
$F_{(6-58)}$=2.828			P=.017						

SD, Standart deviation; *p<0.05

When Table 1 is examined, the intermediate values of agility and speed together show a moderate and significant relationship with leg stiffness (R=476, R^2=.226, $p<0.05$). The mentioned variables together give approximately 23% of the variance in the leg stiffness. According to the standardized regression coefficient (β), when the relative importance order of the predictor variables on leg stiffnes is examined, 0-20 m sprint value has the most significant effect, while 5-10 m sprint value has the least effect. When the t-test results related to the significance of the regression coefficient are examined, it is seen that the variables discussed do not have a significant effect. When the bilateral and partial correlations between the predictor variables and leg stiffnes were examined, low-level and negative relationships were found. Upon examination of the T-test results, it can be concluded that leg stiffness does not

have a significant impact on the changes in speed and agility values. In other words, it can be stated that leg stiffness does not influence the specified parameters. Regression analysis results for predicting leg stiffnes value together with Reactive Strength Index (RSI) values obtained from gymnasts are given in Table 2.

When Table 2 is examined, the RSI values collectively demonstrate a moderate and significant relationship with the leg stiffness. (R=670, R^2=.449, p<0.05). The combined variables account for approximately 45% of the variance in leg stiffnes. The standardized regression coefficient (β) indicates that the RSI obtained from 50 cm has the most significant effect, while the RSI obtained from 30 cm has the least effect when considering the relative importance order of the predictor variables on leg stiffnes. The T-test results regarding the significance of the regression coefficient suggest that the considered variables do not have a significant effect. Upon analyzing the bilateral and partial correlations between the predictor variables and leg stiffnes, moderate and positive relationships were observed. Examination of the T-test results implies that leg stiffness does not significantly impact the changes in Reactive Strength Index (RSI) values. In other words, it can be stated that leg stiffness does not influence the specified parameter.

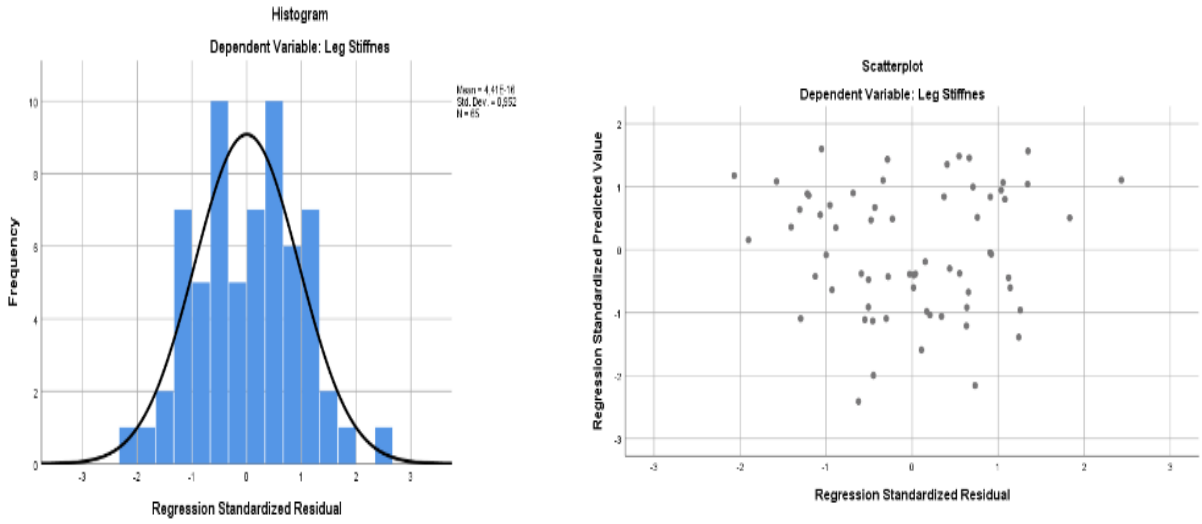


Figure 1. Normality distribution according to histogram test results.

Table 2. *Regression analysis results on predicting leg stiffnes together with RSI values obtained from gymnasts*

Variable	Mean	SD	B	Std Error	β	T	p	Zero-Order	Partial r
Constant			2.487	4.149		.599	.555		
30 cm RSI	1.38	.46	.362	7.080	.024	.051	.960	.545	.011
40 cm RSI	1.46	.48	-6.836	9.790	-.473	-.698	.493	.565	-.151
50 cm RSI	1.55	.50	15.012	8.783	1.070	1.709	.102	.643	.349
60 cm RSI	1.67	.49	-4.169	8.089	-.294	-.515	.612	.581	-.112
20 cm RSI	1.64	.49	4.390	6.550	.306	.670	.510	.606	.145
R=.670			R^2=.449						
$F_{(6-58)}$=3.419			P=.020						

SD, standart deviation; *p<0,05

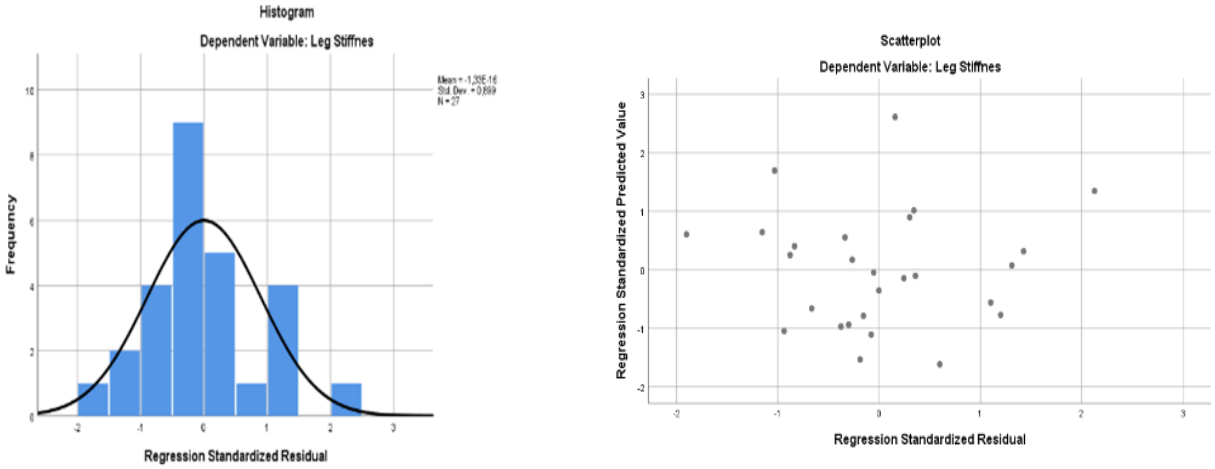


Figure 2. Normality distribution according to histogram test results.

DISCUSSION

In our study, we found a moderately positive correlation between leg stiffnes and RSI values in gymnasts. We found a negative low-level relationship between speed and agility and leg stiffness values.

Leg stiffness can be defined as a mechanical property that determines the efficiency with which the external forces, absorbed by the soft tissues and transmitted to the skeletal system, can be utilised (Riemann et al., 2001: 369-375). Recent studies indicate that during running and jumping activities, tissues such as muscles, tendons and ligaments work in unision with the body's musculoskeletal system, functioning like a single spring by maintaining consistent movement centers. This can be effectively modeled using a simple spring-mass system, incorportaing a linear leg arc and concentrating body mass at the endpoint of that arc (Ferris et al., 1999: 787-794). Despite the complexity of the neuromuscular system, the simplicity of the spring mass model aptly describes the mechanics of all movements involving jumping. (Salsich & Mueller, 2000: 207-216).

Increased leg stiffness during jumping and vertical jump performance has been associated with shorter ground contact times, increased ground contact frequency, and increased vertical ground reaction forces (Arampatzis et all., 2001: 355-364). It has been observed that depth jump 20cm, 40cm and 60cm heigths reach their peak levels with leg stiffness training (Arampatzis et al., 2001: 355-364).

Jumping and leaping are crucial skills that gymnasts need to acquire at an early age, providing them with the ability to perform somersaults, as well as twisted or untwisted double somersaults. A gymnast's jumping ability, especially in ground movements and vaulting, is closely linked to successful performance (Marina et al., 2013: 378-386; Marina et al., 2012: 1879-1886) and is sometimes considered a general indicator of gymnastic proficiency. This ability is defined by the individual's capacity for leaping while successfully executing complex forward and backward rotation sequences (Mkaouer et al., 2012:61-62).

Reactive Strength Index (RSI) was initially defined by Bosco (1985). This metric is calculated by dividing flight time

by ground contact time and was developed to assess the stress on the muscle-tendon complex during activities like depth jumps and plyometric exercises. In gymnastics-related studies, Marina and Jemni (2014) conducted research on elite gymnasts. Over a longitudinal period of 20 months, they implemented incremental plyometric training with drop jumps (DJ) at heights of 20, 40, 60, 80, and 100cm. Before and after the training, they measured flight time, contact time, and power outputs at each height.

The study revealed improvements in flight and contact time durations, and consequently, RSI values, especially in the 80 and 100cm hurdles for elite gymnasts. Based on these findings, they suggested that reducing the time spent on technical routines and initiating 2 to 3 intensive physical conditioning sessions aimed at optimizing gymnasts' plyometric skills would be beneficial.

However, leg stiffness is required for optimum use of the strain-shortening cycle. Adequate leg stiffness ensures efficient use of the elastic energy stored in the musculoskeletal system that emerges during the loading portion of the movement (Maloney & Fletcher, 2018: 109-130). Sert (2016: 76-77), in his study on young tennis players, found a relationship between muscle stiffness of the players and their speed of change of direction in the negative direction at the $p<0.05$ level ($r=0.441$); between speed performance in the positive direction at the $p<0.05$ level ($r= 0.474$), and between jumping performance in the negative direction at the $p<0.05$ level ($r= 0.430$).

In gymnastics, the demonstration of speed involves making rapid changes in the rhythm and tempo of movements, sequentially relaxing and contracting muscles, and showcasing these movements at maximum speed (Hekim & Hekim, 2015:110-115). Additionally, speed can be exhibited by coordinating the movements of various body parts to match the rhythm and tempo of the music. Apart from the application of technical structures in movement presentations, speed in consecutive movements is crucial (Altay & Doğan, 1996).

Several studies have suggested an association between speed and leg stiffness. For example, Rabita et al. (2008:163-171), in their study on French athletes, demonstrated a strong negative relationship between muscle stiffness and jump height. Duran et al. (2010:882-886), in their study on elite male tennis players, reported a positive correlation between leg stiffness and jump height, (CMJ) and 20-meter sprint, but there was no significant correlation between squat jump and 40-meter running speed. Bret et al., (2002:274-281) found that athletes with more vertical stiffness achieved higher acceleration between the first (0-30 m) and second (30-60 m) intervals during the 100 m sprint performance, with greater acceleration between the second and third intervals leading to a slowdown. Girard et al. (2006: 791-796) showed that the decrease in running speed in the last 50m distance range of 100, 200 and 400m sprint performances was accompanied by a decrease in stride length, stride frequency and vertical stiffness, and an increase in ground contact.

CONCLUSION

It can be argued that an increase in leg stiffness positively contributes to both variables measured in gymnasts. The rise in leg stiffness parameters, particularly in the vertical direction, appears to have a greater

impact on the jump parameter compared to speed and agility values. This suggests that the leg stiffness value of the dominant muscle may exhibit more substantial improvement in the jump parameter, given their biomechanical similarity. Consequently, exercises incorporating concentric and eccentric phases, such as plyometric exercises aimed at enhancing the leg stiffness of athletes, could be beneficial additions to training programs, especially in sub-categories like trampoline, rhythmic gymnastics, and artistic gymnastics where jumping is a primary focus.

REFERENCES

Altay, F., & Doğan, F. (1996). Sporty Rhythmic Gymnastics. Unal Ofset, Ankara.

Arampatzis, A., Brüggemann, G.P.& Metzler, V. (1999). The effect of speed on leg stiffness and joint kinetics in human running. *J Biomech*,32,12, 1349-1353.

Arampatzis, A., Schade, F., Walsh, M.& Bruggemann, G.P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr Kinesiol* ,11,355–364.

Bishop, D., Girard, O., & Mendez-Villanueva, A. (2011). Repeated-sprint ability—part II: recommendations for training. Sports medicine, 41, 741-756.

Bompa, T.O& Haff, G.G.(2015). Periodization: Training theory and method. (Translate; Tanju Bagırgan), 5th (ed), (p.315-320),Ankara, *Spor Publishing House and Bookstore.*

Bosco, C. (1985). Elasticita'muscolare e forza esplosiva nelle attivita'fisico-sportive. Sociéta stampa sportiva.

Bret, C., Rahmani, A., Dufour, A.B., Messonnier, L.& Lacour, J.R. (2002). Leg strength and stiffness as ability factors in 100 m sprint running. *J Sports Med Phys Fitness*, 42, 274–281.

Butlar, R.J., Crowell, H.P.& Davis, I.M. (2003). Lower extremity stiffness: implications for performance and injury. *Clin. Biomech,* 18, 6, 511–517.

Dalleau, G., Belli, A., Viale, F., Lacour, J.R& Bourdin M, A. (2004). Simple method for field measurements of leg stiffness in hopping. *Int. J Sports Med,* 25, 3, 170–176.

Duking, P., Born, D.P.& Sperlich, B. (2016). The speedcourt: reliability, usefulness, and validity of a new method to determine change of-direction speed. *Int J Sports Physiol Perform,*11, 130-134.

Duran, S., Ripamonti, M., Beaune, B.& Rahmani, A.(2010). Leg ability faktors in tennis players. *Int J Sports Med,* 31,882-886.

Farley, C.T., Houdijk. H,H., Van Striesn, C.& Louie, M. (1998). Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *J Appl Physiol,* 85, 3,1044-1055.

Ferris, D,P., Liang, K.& Farley, C.T. (1999). Runners adjustlleg stiffness for their first step on a new running surface. *J Biomech,* 32,8,787-794.

Girard, O., Chevalier, R., Leveque, F., Micallef ,J.P.& Millet, G.P.(2006). Specific incremental field test for aerobic fitness in tennis. Br J Sports Med, 40,9,791-796.

Hekim, M., & Hekim, H. (2015). Overview of strength development and strength training in children. Current Pediatrics, 13(2), 110-115.

Lloyd, R., Oliver, J., Hughes, M.& Williams, C. (2012). The effects of 4-weeks of plyometric training on reactivestrength indexand leg stiffness in maleyouths. *J.Strength Cond. Res,* 26, 2812–2819.

Lloyd, R.S., Radnor, J.M., DeSte Croix, M.B.A., Cronin, J.B& Oliver, J.L. (2015). Changes in sprintand jump performances after traditional, plyometric, and combined resistance training in maleyouth pre-and post-peak heightvelocity. *J.Strength Cond. Res,* 30, 1239–1247.

Maloney, S.J & Fletcher, I. M. (2021). Lower limb stiffness testing in athletic performance: a critical review. *Sports Biomech*,20(1), 109-130.

Maloney, S.J.& Fletcher, I.M. (2018). Lower limb stiffness testing in athletic performance: a critical review. *Sports Biomech*,20,1,109-130.

Marina, M., Jemni, M., Rodríguez, F. A., & Jimenez, A. (2012). Plyometric jumping performances of male and female gymnasts from different heights. The Journal of Strength & Conditioning Research, 26(7), 1879-1886.

Marina, M., Jemni, M. ve Rodríguez, F. (2013). Erkek ve kadın jimnastikçilerin atlama performans profili. J Sports Med Phys Fitness , 53 (4), 378-86.

Maquirriain, J. (2013). The interaction between the tennis courtand the player: How does surface affect leg stiffness?. *Sports Biomech*, 12,1,48-53.

Mcneal, J.R., Sands, W.A.& Shultz, B.B.(2007). Muscle activation characteristics of tumbling take-offs. *Sports Biomech*, 6,3, 375-390.

Mkaouer, B., Jemni, M., Amara, S., Chaabèn, H., & Tabka, Z. (2012). Kinematic and kinetic analysis of counter movement jump versus two different types of standing back somersault. Science of Gymnastics Journal, 4(3).

Rabita, G., Couturier, A.& Lambertz, D. (2008). Influence of training background on the relationships between plantar flexor ıntrinsic stiffness and overall musculoskeletal stiffness during hopping. *Eur J Appl Physiol*, 103,2,163-171.

Ramirez-Campillo, R., Thapa, R. K., Afonso, J., Perez-Castilla, A., Bishop, C., Byrne, P. J., & Granacher, U. (2023). Effects of Plyometric Jump Training on the Reactive Strength Index in Healthy Individuals Across the Lifespan: A Systematic Review with Meta-analysis. Sports Medicine, 53(5), 1029-1053.

Riemann, B.L., DeMont, R.G,, Ryu, K.& Lephart SM.(2001). The effects of sex, joint angle, and the gastrocnemius muscle on passive ankle joint complex stiffness. *J Athl Train,*36,4,369-375.

Salsich, G.B.& Mueller, M.J.(2000). Effect of plantar flexor muscle stiffness on selected gait characteristics. *Gait Posture*, 11,207-216.

Sert, V. (2016). Leg strength and stiffness in young tennis players: ıts relationship with speed and agility performance. *Master Thesis*. Sakarya University Institute of Health Sciences.

Sheppard, J.M., Young, W.B., Doyle, T.L.A., Sheppard, T.A & Newton, R.U.(2006). An evaluation of a new test of reactiveagility and its relationship to sprint speed and change of direction speed. *J Sci Med Sport*, 9, 342–349.

Struzık, A. & Zawadzkı, J. (2019). Estimation of potential elastic energy during the countermovement phase of a vertical jump based on the force-displacement curve Estimation of potential elastic energy during the countermovement phase of a vertical jump based on the force-displacement curve. *Acta of Bioengineering and Biomechanics*, 21, 1, 153-160.

Struzik, A., Karamanidis, K., Lorimer, A., Keogh,J.W.L., Gajewski, J. & De Marchis, C. (2021). Application of Leg, Vertical, and Joint Stiffness in Running

Performance: A Literature Overview. *Applied Bionics and Biomechanics,* 2021,1.

Verstegen, M.& Marcello, B. (2001). Agility and coordination. in high performancesports conditioning. B Foran (Eds),(p.139-166), *Champaign: Human Kinetics.*

Young, W. (1995). Laboratory strength assessment of athletes. New studies in athletics, 10, 89-89.

Corresponding author:

Banu KABAK
Center of Athlete Training and Health Research.
banu.kabak@gsb.gov.tr
Phone Number: +905062534738
Fax Number: +90 312 3396847

Article received: 7. 9. 2023
Article accepted: 30. 11. 2023