

Original Research

Hamstring Activity Before and After Break-Point Angle Calculated By Smartphone Application During the Nordic Hamstring Exercise

Toshiaki Soga^{1,2,3}, Shota Yamaguchi⁴, Takayuki Inami⁴, Hiromi Saito¹, Nadaka Hakariya¹, Naoto Nakaichi¹, Sho Shinohara¹, Koki Sasabe¹, Hayato Nakamura¹, Teerapat Laddawong¹, Kei Akiyama⁵, Norikazu Hirose^{5a}

¹ Graduate School of Sport Sciences, Waseda University, ² Graduate School of Engineering and Science, Shibaura Institute of Technology, ³ Japan Society for the Promotion of Science, ⁴ Institute of Physical Education, Keio University, ⁵ Faculty of Sport Sciences, Waseda University

Keywords: Hamstring strain injury, Recurrence prevention, Biceps femoris

<https://doi.org/10.26603/001c.89271>

International Journal of Sports Physical Therapy

Vol. 18, Issue 6, 2023

INTRODUCTION

Previous studies have reported a gradual decrease in biceps femoris (BF) electromyography (EMG) activity after the break-point angle (BPA) during the Nordic hamstring exercise (NHE). However, no investigation has been conducted on BF EMG activity before and after BPA as calculated using a smartphone application (Nordic Angle app).

HYPOTHESIS/PURPOSE

The aim of this study was to investigate the BF EMG activity before and after BPA, as calculated using the Nordic Angle app. The hypotheses were that BF EMG activity would peak near the BPA and gradually diminish afterward.

METHODS

After a warm-up, participants performed three repetitions of prone leg curls to discern maximum voluntary isometric contraction (MVIC) of the hamstrings. The peak value of the BF EMG activity during the prone leg curl was used to convert BF EMG activity during NHE to %MVIC. BPA during NHE was calculated using the Nordic Angle app by analyzing a movie recorded with an iPhone camera. Additionally, the knee flexion angle during NHE was determined using two-dimensional motion analysis software based on video data. To compare EMG activity before and after BPA calculated by the Nordic Angle app, the knee flexion angle was divided into seven phases: 10-15° before BPA, 5-10° before BPA, BPA ± 5°, 5-10° after BPA, 10-15° after BPA, 15-20° after BPA, and 20-25° after BPA.

RESULTS

There was no significant difference between the BPA of the Nordic angle and the knee flexion angle at peak BF EMG activity ($d = 0.13$, $p = 0.678$). The BF EMG activity at 20-25° after BPA was significantly lower than the BF EMG activity at BPA ± 5° ($d = 0.87$, $p = 0.011$).

CONCLUSIONS

To prevent the recurrence of hamstring injuries, it is important to incorporate knee flexion exercises that enhance BF EMG activity at 15-35° of knee flexion (0° indicates a fully extended knee). Thus, it is recommended to keep the BPA of the Nordic Angle within 35° to effectively prevent recurrent hamstring injuries during NHE.

a Corresponding author:
Norikazu Hirose
Faculty of Sport Sciences, Waseda University, Japan
Email: toitsu_hirose@waseda.jp

Level of evidence

3b

INTRODUCTION

Hamstring injuries are prevalent in football (soccer), a sport characterized by high-speed running.¹ Previous study have shown that the incidence of hamstring injuries has doubled from 12% to 24% between 2001 and 2022.¹ Additionally, more than 50% of athletes with prior hamstring injury experience a recurrence of hamstring injury within 25 days of returning to play.² Considering that players typically resume full team training in approximately 20 days,³ it is imperative to not only prevent initial hamstring injury but also reduce the risk of recurrence for improved athletic performance in football.

The biceps femoris (BF) muscle is primarily affected during high-speed running, making it susceptible to hamstring injuries.^{4,5} Individuals with a history of hamstring injury often exhibit inhibited BF electromyography (EMG) activity during isokinetic knee flexion exercises.⁶⁻⁸ Notably, the reduction in BF EMG activity is particularly prominent at knee flexion angles of 15-35° (0° indicates a fully extended knee),⁶⁻⁸ which align with the angles at which hamstring injuries commonly occur.^{9,10} It has also been reported that isokinetic knee flexion training incorporating eccentric loading up to 20° knee flexion can effectively prevent recurrent hamstring injuries.¹¹ Therefore, the implementation of knee flexion exercises that enhance BF EMG activity at angles of 15-35° might play a crucial role in preventing the recurrence of hamstring injuries.

The Nordic hamstring exercise (NHE) is one such exercise used to improve eccentric knee flexion strength.¹² It involves maintaining a straight posture from the knees to the head while leaning the upper body forward to a level that the hamstring muscles can tolerate. The knee flexion angle at which the knee flexor strength cannot resist the external knee flexion moment accompanying the forward leaning of the trunk is referred to as the break-point angle (BPA). Given that the BPA is approximately 50° even in trained soccer players,¹³ BF EMG activity at 15-35° knee flexion angle is likely diminished with standard NHE in many athletes.¹⁴⁻¹⁶

The recent development of a smartphone application (Nordic Angle) has introduced the automatic calculation of BPA, eliminating the need to import data to a personal computer. Although it has been reported that BF EMG activity peaks near the BPA and gradually diminishes afterward,¹⁶ the investigation of BF EMG activity before and after BPA, as calculated by the Nordic Angle, remains unexplored. If the BPA value obtained using the Nordic Angle determines whether BF EMG activity is enhanced at knee flexion angles of 15-35°, it could significantly benefit the field of sports medicine. Additionally, if the angle of the lower leg slope for NHE can be adjusted based on the BPA value calculated by the Nordic Angle, it may further optimize BF EMG activity at knee flexion angles of 15-35°.^{16,17}

Therefore, the aim of this study was to investigate the BF EMG activity before and after BPA, as calculated using

the Nordic Angle app. A secondary purpose was reassess the validity of the Nordic Angle app¹⁸ by comparing its BPA values with those obtained through motion analysis. The hypotheses were that BF EMG activity would peak near the BPA and gradually diminish afterward, and that the BPA calculated using the Nordic Angle would demonstrate high validity.

METHODS

STUDY DESIGN

After a warm-up, the participants underwent three repetitions of the prone leg curl with maximum voluntary isometric contraction (MVIC). The peak value of BF EMG activity during the prone leg curl was used to convert the BF EMG activity during NHE to %MVIC. The participants then performed three NHE repetitions, which were recorded using an iPhone 12 high-speed camera. The BPA during NHE was calculated using two-dimensional motion analysis software and the Nordic Angle application ([Figure 1](#)). To quantify BF EMG activity before and after BPA, EMG and kinematic data from the motion analysis were synchronized. To compare BF EMG activity before and after BPA calculated by Nordic Angle, the knee flexion angle was divided into seven phases (10-15° before BPA, 5-10° before BPA, BPA ± 5°, 5-10° after BPA, 10-15° after BPA, 15-20° after BPA, and 20-25° after BPA), where 0° represented the fully extended position of the knee. The Friedman test was employed to compare the BF EMG activity in these seven phases. The validity of the Nordic Angle data was examined using the Pearson correlation coefficient test for consistency with the motion analysis data, and the agreement between these measurements was examined using the Bland-Altman analysis.

PARTICIPANTS

The sample size was calculated a priori based on Pearson's correlation coefficient analysis (G*Power version 3.1, Heinrich Heine Universität, Düsseldorf, Germany). The input parameters (correlation ρ H1 = 0.75, alpha = 0.05, and power = 0.8) were set with reference to the effect size of a previous study.¹⁸ This setting resulted in a sample size of 11 participants. Therefore, 13 male volunteers majoring in sports science (age, 25.2 ± 2.6 years; height, 174.3 ± 5.1 cm; and body mass, 70.5 ± 8.2 kg; all measured in mean ± standard deviation [SD]) participated in this study. Inclusion criteria included healthy males aged of 18-35 years engaged in sports activities without musculoskeletal pain, while the exclusion criterion was the inability to perform NHE due to lower extremity injury. The experimental protocol was approved by the institutional review board of Waseda University's ethical committee (approval number: 2022-531), and all procedures adhered to the principles of the Declaration of Helsinki. Informed consent was obtained from all partici-

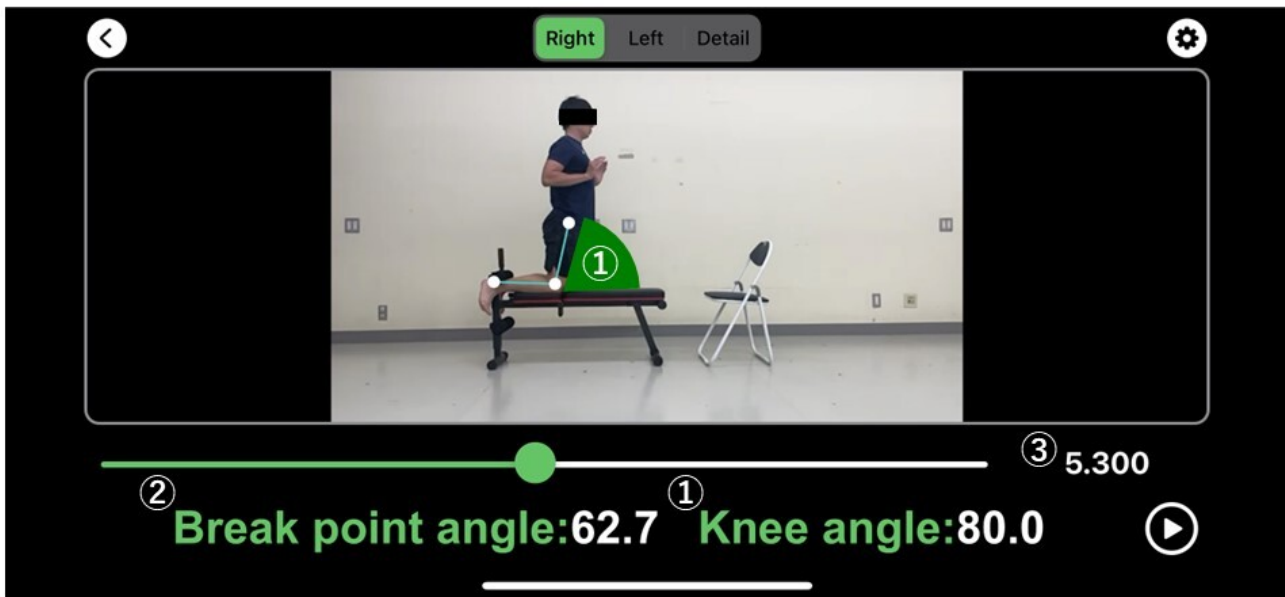


Figure 1. Nordic Angle screen information during the Nordic hamstring exercise. 1: Knee flexion angle (0° indicates the fully extended position of the knee.); 2: BPA determined by the Nordic Angle; 3: Current time from the movie data start.

pants after providing them with detailed information about the study.

PROCEDURES

Participants performed a warm-up comprising light aerobic activity (2 min of alternating stepping on a 15-cm high box), a 15-second static hamstring stretch (standing hamstring stretch on one leg), and 1 set of 10 repetitions of dynamic hamstring stretching (forward leg swing). Hamstring stretching was performed on both legs. After the warm-up, surface EMG electrodes were attached to the BF of the right leg, and participants completed three repetitions of the prone leg curl with MVIC. The knee flexion angle during the prone leg curl was 30° and was performed against manual resistance.¹⁹ EMG measurements were performed with reference to “Standards for Reporting EMG Data”.²⁰ The examiner instructed the participants to reach maximal effort for 2 s and then maintain it for 2 s in each MVIC.²¹ There was at least 1 min of rest between each MVIC trial. The participants then performed three NHE trials with two additional familiarized repetitions before the trials. There was at least 2 min of rest between each NHE trial. The experiment was conducted under the supervision of a National Strength and Conditioning Association Certified Strength and Conditioning Specialist.

NORDIC HAMSTRING EXERCISE

Participants assumed a kneeling position on a bench of approximately 50 cm, with their elbows bent and hands open in front of them (Figure 1). They were instructed to lean forward slowly while maintaining a straight posture from the knee to the head. A certified examiner ensured correct execution of the NHE.

ELECTROMYOGRAPHY

The EMG signal was sampled at 1000 Hz and bandpass-filtered (10-450 Hz) using a wireless telemetry and surface EMG silver electrodes (DL-5000 with m-Biolog2; S&ME Inc., Tokyo, Japan). The electrode had a bar length of 1 cm, bar width of 0.1 cm, and distance of 1 cm between the recording sites. The participants' skin was shaved the hair around the target site and cleaned using cotton dampened with alcohol to reduce noise. BF electrode placement was midpoint between the ischial tuberosity and the lateral condyle of the tibia.²² Participants were verbally encouraged to ensure maximal effort. Peak EMG activity during the prone leg curl and NHE was calculated based on the peak root mean square (RMS) value. The RMS value was computed for a 100 ms window.

TWO-DIMENSIONAL MOTION ANALYSIS

The iPhone 12 camera was set to 240 fps, and the camera was positioned approximately 3 m from the right side of the participants at a height of approximately 0.9 m. After transferring the recorded movie to a personal computer, two-dimensional motion analysis was performed using motion analysis software (Frame-DIAS V; DKH Inc., Tokyo, Japan). Reflective markers were attached to the greater trochanter, lateral epicondyle of the femur, and the lateral malleolus to calculate the knee flexion angle through digitization. The knee flexion angle was defined as an anatomical angle with a value of 0° , indicating full knee extension. In addition, the knee extension angular velocity was calculated based on the knee flexion angle and time.¹⁸

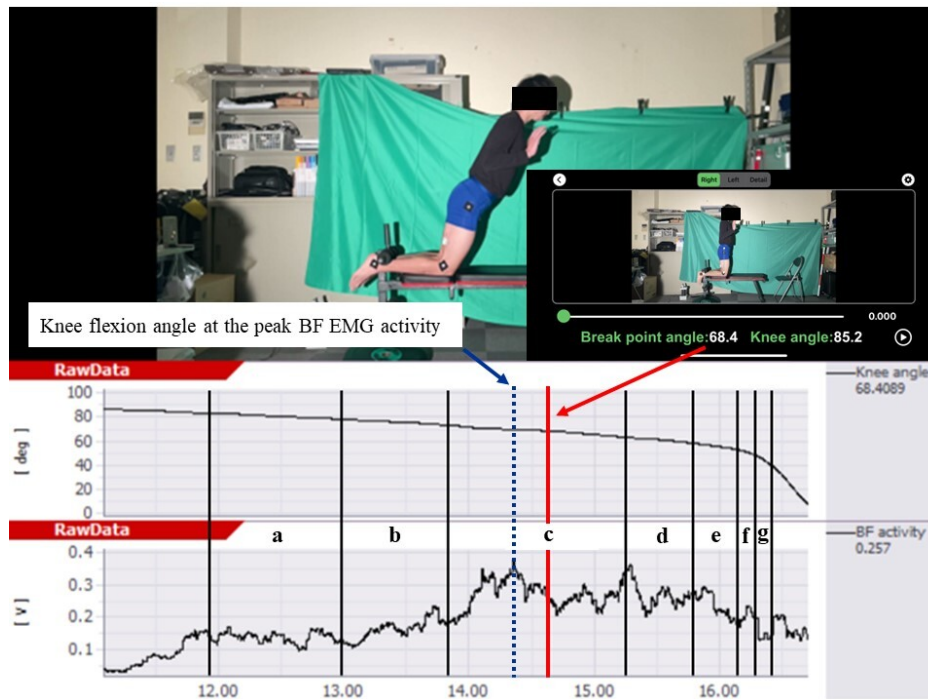


Figure 2. The BF EMG activity before and after BPA calculated by the Nordic Angle. a: 10-15° before BPA; b: 5-10° before BPA; c: BPA \pm 5°; d: 5-10° after BPA; e: 10-15° after BPA; f: 15-20° after BPA; g: 20-25° after BPA. The solid red line shows the BPA of the Nordic Angle, and the dashed blue line shows the knee flexion angle at the peak BF EMG activity.

DATA ANALYSIS

Kinematic data obtained through motion analysis were smoothed using a Butterworth low-pass filter with a cut-off frequency of 6 Hz. BPA for two-dimensional motion analysis was defined as the knee flexion angle at which the knee extension angular velocity exceeded 30°/s.¹⁸ The average BPA values from the motion analysis and the Nordic Angle were calculated from the BPA values of the three NHE trials.

To calculate the knee flexion angle at the peak BF EMG activity, BF EMG activity and knee flexion were synchronized using a trigger mechanism with a synchronization lamp (TRIAS; DKH Inc., Tokyo, Japan) (Figure 2). To assess the BF EMG activity before and after BPA calculated using the Nordic Angle, the knee flexion angle was divided into seven phases (Figure 2). The average BF EMG activity in the seven phases before and after the BPA was calculated from the BF EMG activity values of the three NHE trials.

STATISTICAL ANALYSIS

Values are expressed as mean \pm SD. The Shapiro-Wilk test was used to assess normality. Normality was confirmed for BPA calculated by both Nordic Angle and motion analyses, whereas normality was not confirmed for one of the BF EMG activities in the seven knee flexion angle ranges. Differences in BF EMG activity in seven phases (10-15° before BPA, 15-10° before BPA, BPA \pm 5°, 5-10° after BPA, 10-15° after BPA, 15-20° after BPA, 20-25° after BPA) before and after BPA were compared using Friedman test. The paired

t-test was performed to confirm the difference in BPA calculated by the Nordic Angle and the knee flexion angle at peak BF EMG activity. Cohen's d was classified based on the following effect size criteria: trivial, <0.2; small, 0.2 to 0.49; medium, 0.5 to 0.79; and large, >0.8. The validity of the Nordic Angle data was examined using the Pearson correlation test for consistency with the motion analysis data. The magnitude of the correlation was established based on the following criteria: $r_s = 1$, perfect correlation; $1 \geq r \geq 0.9$, nearly perfect; $0.9 \geq r \geq 0.7$, very large; $0.7 \geq r \geq 0.5$, large; $0.5 \geq r \geq 0.3$, moderate; $0.3 \geq r \geq 0.1$, small; and $0.1 \leq r$, trivial. The agreement between the Nordic Angle and motion analysis was examined using the Bland-Altman analysis. The paired t-test was performed to confirm the difference in BPA between the Nordic Angle and motion analysis data. The limits of agreement in the Bland-Altman analysis were calculated by multiplying SD by ± 1.96 .²⁵ Statistical analyses were performed using SPSS version 29 (IBM SPSS, Armonk, NY, USA). The significance level was set at $p < 0.05$.

RESULTS

THE BF EMG ACTIVITY IN SEVEN PHASES BEFORE AND AFTER BREAK-POINT ANGLE

The BPA values of the Nordic Angle and knee flexion angle at the peak BF EMG activity were $61.6 \pm 10.7^\circ$ and $62.9 \pm 9.9^\circ$, respectively, with no significant difference observed between the two ($d = 0.13$, $p = 0.678$).

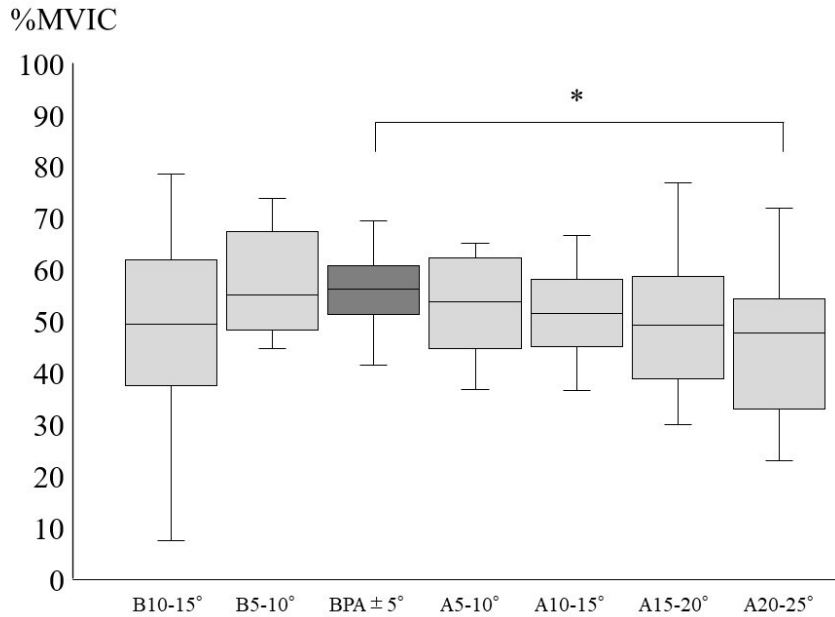


Figure 3. The BF EMG activity before and after BPA.

Abbreviations: B10-15°, 10-15° before BPA; B5-10°, 5-10° before BPA; BPA ± 5°; A5-10°, 5-10° after BPA; A10-15°, 10-15° after BPA; A15-20°, 15-20° after BPA 20; A20-25°, 20-25° after BPA. The symbols * BPA ± 5° vs. A20-25° indicates statistically significant difference ($d = 0.87$, $p = 0.011$).

Figure 3 shows the BF EMG activity magnitude before and after BPA, as calculated using the Nordic Angle. The BF EMG activity at 20-25° after BPA was significantly lower than at BPA ± 5° ($d = 0.87$, $p = 0.011$).

THE VALIDITY OF THE NORDIC ANGLE

Figure 4 shows the correlation between the BPA of the Nordic Angle and the motion analysis. The Pearson correlation between the Nordic angle and the angle determined using motion analysis was nearly perfect ($r = 0.92$, $p < 0.001$).

Figure 5 shows the agreement between the BPA of the Nordic Angle and motion analysis. The BPAs obtained from the Nordic Angle and motion analysis were $61.6 \pm 10.7^\circ$ and $58.7 \pm 11.2^\circ$, respectively, indicating a significant difference between the two datasets ($d = 0.27$, $p = 0.029$). The mean difference between the Nordic Angle and motion analysis values was $3.0 \pm 4.3^\circ$, with the limits of agreement ranging from -5.5° to 11.4° .

DISCUSSION

The investigation of BF EMG activity before and after BPA, as calculated by the Nordic Angle, remains unexplored. In addition, there is no verification of the validity of Nordic Angle. Therefore, this study aimed to investigate the BF EMG activity before and after BPA, calculated using the Nordic Angle. In addition, it sought to re-examine the validity of the Nordic Angle by comparing the BPA values with motion analysis. The main outcomes are as follows: (a) No significant difference between the BPA of Nordic Angle and

knee flexion angle at the peak BF EMG activity ($d = 0.13$, $p = 0.678$); (b) The BF EMG activity at 20-25° after BPA was significantly lower than the BF EMG activity at BPA ± 5° ($d = 0.87$, $p = 0.011$); (c) The Pearson correlation between the Nordic angle and the angle determined using motion analysis was perfect ($r = 0.92$, $p < 0.001$); (d) A significant difference between mean BPA values of the Nordic Angle and motion analysis was $3.0 \pm 4.3^\circ$ ($d = 0.27$, $p = 0.029$), and the limits of agreement ranged from -5.5 to 11.4 showing there was no statistical difference and good agreement between the two methods of measurement. These results supported the hypothesis.

Specifically, there was no significant difference between the BPA calculated using the Nordic Angle and the knee flexion angle at peak BF EMG activity ($d = 0.13$, $p = 0.678$), indicating that BF EMG activity peaked near the BPA. In addition, the BF EMG activity at 20-25° after BPA was significantly lower than that at BPA ± 5° ($d = 0.87$, $p = 0.011$) (Figure 3). This suggests that high BF EMG activity is maintained up to 20° after BPA, but it significantly decreases beyond 20° of BPA as calculated by the Nordic Angle. Soga et al. investigated the magnitude of BF EMG activity before and after BPA calculated by motion analysis during NHE variations with different lower leg slope angles.¹⁶ They reported that BF EMG activity peaks near the BPA during NHE variations with 20° or 40° lower leg slope, and decreases toward the shallow knee flexion position during NHE variations with 0° lower leg slope (similar to standard NHE). The results of this study support these findings, emphasizing the importance of knee flexion exercises that enhance BF EMG activity at 15-35° knee flexion to effectively prevent recurrent hamstring injuries, the BPA of the Nordic

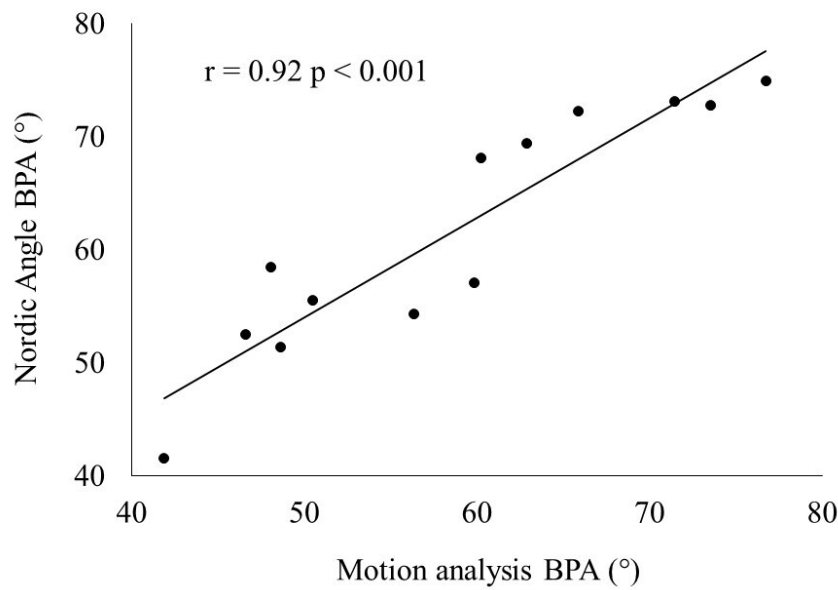


Figure 4. The correlation between the BPA obtained from the Nordic Angle and that determined through motion analysis.

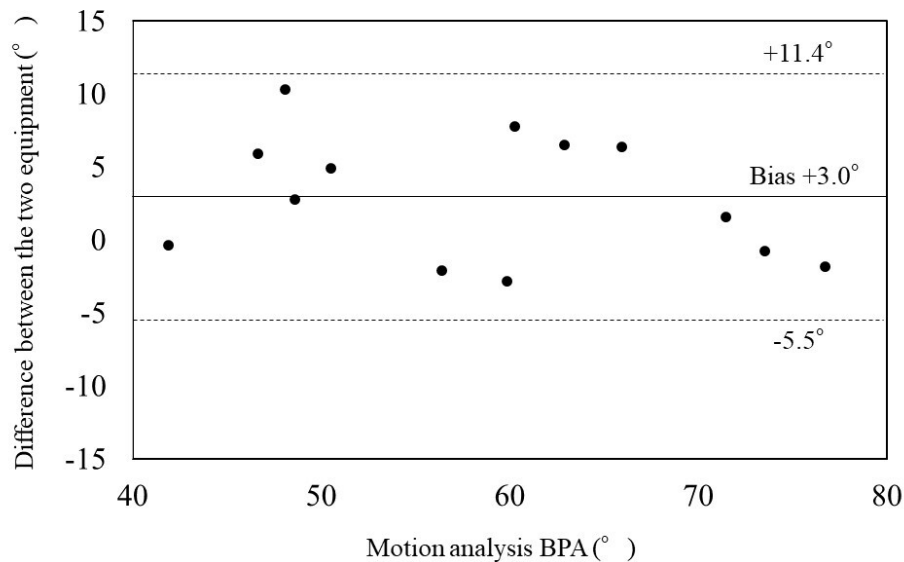


Figure 5. The agreement between BPA of the Nordic Angle and that of motion analysis, along with the limits of agreement.

The solid line shows the difference between the mean values of the Nordic Angle and motion analysis, and the dotted line shows the mean values of motion analysis.

Angle should be kept within 35° to be effective in preventing recurrent hamstring injuries with standard NHE. Since the BPA is approximately 50° even for trained soccer players,¹³ incorporating lower leg slope assistance during NHE might be necessary to enhance its efficacy in preventing

hamstring injuries in many athletes. The BPA changes proportionally with the angle of the lower leg slope,^{16,17} so if the Nordic Angle calculates a BPA of 75° , setting the lower leg slope angle to 40° would theoretically result in a BPA of 35° .

This study also assessed the validity of the Nordic Angle's BPA determination. The findings confirmed a nearly perfect correlation between the BPA of the Nordic Angle and the BPA determined by motion analysis ($r = 0.92$, $p < 0.001$) (Figure 4). Comparatively, a previous study by Soga et al. using similar methodology did not achieve statistical significance in Spearman correlation ($p = 0.052$),¹⁸ but reported a very large correlation ($r_s = 0.75$). They attributed the lack of significant differences to a small sample size ($n = 7$). In contrast, the current study with a larger sample size ($n = 13$) revealed a nearly perfect correlation, demonstrating that the Nordic Angle not only exhibits perfect reliability¹⁸ but also has high validity.

The results of this study revealed a significant difference between the mean BPA values of the Nordic Angle and motion analysis, amounting to $3.0 \pm 4.3^\circ$ ($d = 0.27$, $p = 0.029$), with the limits of agreement ranging from -5.5° to 11.4° (Figure 5). These findings slightly differ from those of a previous study conducted by Soga et al., who compared the mean BPA of the Nordic Angle with the BPA of motion analysis using a methodology similar to that applied in this study. Their reported difference between the BPA of the Nordic Angle and motion analysis was $0.4 \pm 2.1^\circ$, which was not significantly significant. This discrepancy in results might be partly attributed to the different digitization locations used in the two studies. In the previous study, the knee flexion angle was calculated by digitizing the greater trochanter, center of the knee joint, and lateral malleolus, whereas in this study, it was calculated by digitizing greater trochanter, lateral epicondyle of the femur, and lateral malleolus. Although this variation might be responsible for the observed significant difference in BPA values, the small discrepancy of approximately 3° ($d = 0.27$, $p = 0.029$) is not a major concern. Furthermore, Soga et al. reported that the limits of agreement ranged from -3.9° to 4.6° ¹⁸ in their previous study,¹⁸ whereas in the present study, the limits of agreement were wider. This disparity in results could be attributed to the number of NHE trials conducted, with the previous study utilizing 12 trials, while the current study employed only three trials. It is likely that the variation in the number of trials affected the measurement precision. Therefore, it is recommended to perform BPA measurements using the Nordic Angle with at least 5 trials and calculate the average for improved accuracy.

This study has four limitations. First, the measurement method was limited to a two-dimensional motion analysis. It is crucial for future research to examine the validity of three-dimensional motion analysis to enhance the comprehensiveness of findings. Second, the data collected from repeated trials within a single day hindered the ability to

draw conclusions about inter-session testing. Third, because the EMG electrodes were placed without the use of ultrasound etc., there may have been some crosstalk with other hamstring muscles. Finally, the age of the participants was 25.2 ± 2.6 years. This limits the generalizability of the findings of this study.

CONCLUSIONS

The results of this study indicate that BF EMG activity at $20\text{--}25^\circ$ after BPA was significantly lower than at $BPA \pm 5^\circ$ ($d = 0.87$, $p = 0.011$) and that there were no significant differences between BPA angles measured by the Nordic app and knee flexion angle at the peak BF EMG activity, and the correlations between these measures were nearly perfect. However, the mean difference between the Nordic Angle and motion analysis values was $3.0 \pm 4.3^\circ$, with the limits of agreement ranging from -5.5° to 11.4° .

ACKNOWLEDGMENTS

The authors would like to acknowledge the Graduate School of Sport Sciences, Waseda University for the valuable support and assistance provided throughout this study. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author, who was involved in organizing the study. This work was supported by both JST SPRING (Grant Number: JPMJSP2128) and JSPS KAKENHI (Grant Number: JP23KJ1988).

CONFLICT OF INTEREST DECLARATION

Nordic Angle is a smartphone application developed in collaboration with S-CADE. Co., Ltd. and Athletic Training Laboratory at Waseda University (instructed by Professor Norikazu Hirose). The first author of the article collected and analyzed the data. However, the authors of the current study assert no conflicts as they do not receive any fees from S-CADE. Co., Ltd. for developing the Nordic Angle, and the installation of the Nordic Angle app is free.

Submitted: July 24, 2023 CST, Accepted: September 26, 2023 CST

© The Author(s)



This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CCBY-NC-4.0). View this license's legal deed at <https://creativecommons.org/licenses/by-nc/4.0> and legal code at <https://creativecommons.org/licenses/by-nc/4.0/legalcode> for more information.

REFERENCES

1. Ekstrand J, Bengtsson H, Waldén M, Davison M, Khan KM, Hägglund M. Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22. *Br J Sports Med.* 2022;57(5):292-298. doi:10.1136/bjsports-2021-105407
2. Wangensteen A, Tol JL, Witvrouw E, et al. Hamstring reinjuries occur at the same location and early after return to sport: a descriptive study of MRI-confirmed reinjuries. *Am J Sports Med.* 2016;44(8):2112-2121. doi:10.1177/0363546516646086
3. Ekstrand J, Healy JC, Waldén M, Lee JC, English B, Hägglund M. Hamstring muscle injuries in professional football: the correlation of MRI findings with return to play. *Br J Sports Med.* 2012;46(2):112-117. doi:10.1136/bjsports-2011-090155
4. Askling CM, Tengvar M, Tarassova O, Thorstensson A. Acute hamstring injuries in Swedish elite sprinters and jumpers: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. *Br J Sports Med.* 2014;48(7):532-539. doi:10.1136/bjsports-2013-093214
5. Askling CM, Tengvar M, Thorstensson A. Acute hamstring injuries in Swedish elite football: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. *Br J Sports Med.* 2013;47(15):953-959. doi:10.1136/bjsports-2013-092165
6. Buhmann R, Trajano GS, Kerr G, Shield A. Voluntary Activation and Reflex Responses after Hamstring Strain Injury. *Med Sci Sports Exerc.* 2020;52(9):1862-1869. doi:10.1249/mss.0000000000002327
7. Opar DA, Williams MD, Timmins RG, Dear NM, Shield AJ. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. *J Electromyogr Kinesiol.* 2013;23(3):696-703. doi:10.1016/j.jelekin.2012.11.004
8. Sole G, Milosavljevic S, Nicholson HD, Sullivan SJ. Selective strength loss and decreased muscle activity in hamstring injury. *J Orthop Sports Phys Ther.* 2011;41(5):354-363. doi:10.2519/jospt.2011.3268
9. Guex K, Gojanovic B, Millet GP. Influence of hip-flexion angle on hamstrings isokinetic activity in sprinters. *J Athl Train.* 2012;47(4):390-395. doi:10.4085/1062-6050-47.4.04
10. Miyamoto N, Hirata K. Site-specific features of active muscle stiffness and proximal aponeurosis strain in biceps femoris long head. *Scand J Med Sci Sports.* 2021;31(8):1666-1673. doi:10.1111/sms.13973
11. Tyler TF, Schmitt BM, Nicholas SJ, McHugh MP. Rehabilitation After Hamstring-Strain Injury Emphasizing Eccentric Strengthening at Long Muscle Lengths: Results of Long-Term Follow-Up. *J Sport Rehabil.* 2017;26(2):131-140. doi:10.1123/jsr.2015-0099
12. Medeiros DM, Marchiori C, Baroni BM. Effect of Nordic Hamstring Exercise Training on Knee Flexors Eccentric Strength and Fascicle Length: A Systematic Review and Meta-Analysis. *J Sport Rehabil.* 2020;30(3):482-491. doi:10.1123/jsr.2019-0388
13. Lee JWY, Cai MJ, Yung PSH, Chan KM. Reliability, Validity, and Sensitivity of a Novel Smartphone-Based Eccentric Hamstring Strength Test in Professional Football Players. *Int J Sports Physiol Perform.* 2018;13(5):620-624. doi:10.1123/ijcpp.2017-0336
14. Ditroilo M, De Vito G, Delahunt E. Kinematic and electromyographic analysis of the Nordic Hamstring Exercise. *J Electromyogr Kinesiol.* 2013;23(5):1111-1118. doi:10.1016/j.jelekin.2013.05.008
15. Monajati A, Larumbe-Zabala E, Goss-Sampson M, Naclerio F. Analysis of the Hamstring Muscle Activation During two Injury Prevention Exercises. *J Hum Kinet.* 2017;60(1):29-37. doi:10.1515/hukin-2017-0105
16. Soga T, Nishiumi D, Furusho A, Akiyama K, Hirose N. Effect of Different Slopes of the Lower Leg during the Nordic Hamstring Exercise on Hamstring Electromyography Activity. *J Sports Sci Med.* 2021;20(2):216-221. doi:10.52082/jssm.2021.216
17. Soga T, Keerasomboon T, Akiyama K, Hirose N. Difference of Hamstring Activity Between Bilateral and Unilateral Nordic Hamstring Exercises With a Sloped Platform. *J Sport Rehabil.* 2022;31(3):325-330. doi:10.26603/001c.83936
18. Soga T, Yamaguchi S, Inami T, et al. The Validity and Reliability of a Smartphone Application for Break-Point Angle Measurement during Nordic Hamstring Exercise. *Int J Sports Phys Ther.* 2023;18(4):917-922. doi:10.1123/jsr.2021-0249

19. Hirose N, Tsuruike M. Differences in the electromyographic activity of the hamstring, gluteus maximus, and erector spinae muscles in a variety of kinetic changes. *J Strength Cond Res*. 2018;32(12):3357-3363. [doi:10.1519/jsc.00000000000002747](https://doi.org/10.1519/jsc.00000000000002747)

20. Merletti R, Di Torino P. Standards for reporting EMG data. *J Electromyogr Kinesiol*. 1999;9(1):3-4.

21. Hegyi A, Csala D, Kovács B, et al. Superimposing hip extension on knee flexion evokes higher activation in biceps femoris than knee flexion alone. *J Electromyogr Kinesiol*. 2021;58:102541. [doi:10.1016/j.jelekin.2021.102541](https://doi.org/10.1016/j.jelekin.2021.102541)

22. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol*. 2000;10(5):361-374. [doi:10.1016/s1050-6411\(00\)00027-4](https://doi.org/10.1016/s1050-6411(00)00027-4)

23. Balsalobre-Fernández C, Glaister M, Lockey RA. The validity and reliability of an iPhone app for measuring vertical jump performance. *J Sports Sci*. 2015;33(15):1574-1579. [doi:10.1080/02640414.2014.996184](https://doi.org/10.1080/02640414.2014.996184)