EFFECT OF A SIX-WEEK NEUROMUSCULAR TRAINING PROGRAM ON VERTICAL STIFFNESS IN HEALTHY HIGH SCHOOL DISTANCE RUNNERS

Colin W. Bond[1], Kevin P. Feltz[1], Madison Crabtree[1], Janell K. Burkart[1], Zadok Isaacs[1], Jenny Dalland[1], Melissa Moyer[1], Lisa N. MacFadden[1]

[1]Sanford Sports Science Institute, Sioux Falls, SD

Athletes, coaches, and health care teams know that preventing running-related injuries (RRI) and improving running performance are extremely important. Proactive neuromuscular training (NMT) is often included as a complement to running programs for this reason. The purpose of this study was to evaluate the effect of proactive six-week low-intensity NMT focused on proximal hip and thigh muscles on healthy high-school runners' muscle strength, biomechanical stiffness, peak ground reaction force, cadence, and stride length. The study demonstrates that the NMT increased a runner's total strength by 10.4% and knee extensor strength by 10.3%, showed no change in stiffness, cadence, or stride length, and showed a decrease in ground reaction force post-program by 1.3%. Results show the multivariable nature of RRI risk, and prompt further, more generalizable, evaluation.

KEYWORDS: running, injury, prevention, training, strength

INTRODUCTION: Preventing running-related injury (RRI) and improving running performance are two goals of runners, coaches, and health care teams (Messier et al., 2008). Neuromuscular training (NMT), often performed as a warm-up prior to a run, is a proactive complement to a running program for healthy runners. Biomechanical properties that may be influenced by NMT and associated with RRI risk and performance are stiffness, ground reaction forces, muscle strength, stride length, and cadence (Butler et al., 2006; Ford et al., 2015; van der Worp et al., 2016). Baseline weakness of the proximal hip and thigh muscles is associated with subsequent RRI. (Messier et al., 2008) Proximal weakness can cause faulty proximal hip mechanics that, in turn, cause biomechanical aberrancies distally, such as dynamic knee valgus or excessive pronation (Morin et al., 2005; Snyder et al., 2009; van der Worp et al., 2016). Therefore, it is no surprise that an NMT focused on these muscles is considered essential in reducing RRI risk and increasing performance (Ford et al., 2015). A runner's leg can be modeled as a deformable spring supporting a point mass, which allows for macroscopic assessments of stiffness (Blum et al., 2009; Butler et al., 2003). Vertical stiffness ($\hat{k}_{vert}$) is one macroscopic measurement of stiffness (Blum et al., 2009; Morin et al., 2005). High $\hat{k}_{vert}$ can cause poor attenuation of repetitive forces, potentially increasing RRI risk, and low stiffness can cause poor utilization of the stretch-shortening cycle, potentially reducing running economy (Blum et al., 2009; Butler et al., 2003). High peak vertical ground reaction forces ($vGRF_{peak}$) are also associated with high $\hat{k}_{vert}$ and commonly thought, albeit without solid evidence, to be a risk factor for RRI (van der Worp et al., 2016). Stride length and cadence are also thought to be related to RRI risk and performance (Napier et al., 2015; Schubert et al., 2014). Increasing cadence by 5% to 10% for a given running speed has been proposed to reduce RRI risk due to the accompanying reduction in stride length, which may alter $vGRF_{peak}$ and $\hat{k}_{vert}$ (Schubert et al., 2014). NMT by nature increases a runner's internal extension moment capacity, which, if unaccompanied by another running-specific intervention, potentially increases $vGRF_{peak}$ and $\hat{k}_{vert}$ at a given running speed. Ultimately, muscle strength and biomechanics form a complex relationship. There is a lack of literature on the effects of NMT on biomechanics in young runners specifically, a demographic more prone to overuse injury than non-runner peers. The primary purpose of this study was to evaluate the effect of a proactive six-week low-intensity NMT on healthy high-school runner's skeletal muscle strength, $\hat{k}_{vert}, vGRF_{peak}$, cadence, and stride. It was hypothesized that the NMT and running program would improve muscle strength, increase $\hat{k}_{vert}$ and $vGRF_{peak}$, and do not affect cadence and stride length.

METHODS: Twenty-nine high-school male (n = 18) and female (n = 11) runners (15.6 ± 1.4 y, 60.0 ± 10.7 kg, 1.68 ± 0.18 m) participated in this study, which was conducted after Institutional Review Board approval. Runners' strength and biomechanics were assessed before (PRE) and after (POST) the six-week NMT. Guided and supervised NMT was completed two times per week for twenty-five minutes per session for six weeks concurrently with a running program. The NMT included low-resistance strength, plyometric, balance, and agility drills similar to those completed as part of a knee injury prevention program. This enabled the runners to continue high-intensity running as part of their normal training program and reflected elements of a program that could easily be completed as part of a pre-run warm-up. The runners' hip abduction, hip extension, and knee extension peak isometric torques were assessed using a dynamometer (Biodex Multi-Joint System Pro, Shirley, NY, USA). Mean peak isometric torque from three trials were averaged between the left and right legs and was used as an indicator of strength. To assess biomechanics, runners completed a two-mile run at self-selected running speed, followed by an additional one-mile run on a pressure-instrumented treadmill (H/P/Cosmos Zebris Medical GmbH FDM-T, Nussdorf, Germany). The speed chosen at PRE and POST was matched. Plantar pressure magnitude data was collected at 100 Hz, the maximal allowed by the treadmill, for the final 30 seconds of the third mile. The $\hat{k}_{vert}$ and $vGRF_{peak}$ were estimated using the runner's contact and flight times, horizontal running speed, and body mass using previously validated equations (Morin et al., 2005). The runner's cadence and stride length were also computed. The $\hat{k}_{vert}$, $vGRF_{peak}$, and hip extension, hip abduction, and knee extension peak torques were normalized to the runner's body mass, and stride length was normalized to the runner's leg length. The dependent continuous variables were $\hat{k}_{vert}$, $vGRF_{peak}$, hip abduction, hip extension, and knee extension strength, cadence, and stride length. Independent categorical variables included time and muscle group. Linear mixed-effects models where time was a random effect and each runner was assigned a random slope and intercept were completed using SPSS (IBM SPSS v. 26, Armonk, NY, USA). Bonferroni corrected post-hoc tests were used to evaluate the source of any significant effects. Significance was initially set to p < .05.

RESULTS: Time (F = 6.96, p = .023) and muscle group (F = 283.9, p < .001) were significant suggesting strength changed from PRE to POST and that one muscle was stronger than another but time × muscle group was not significant (F = 1.00, p = .372) suggesting that the strength of all muscles changed similarly over time. Overall strength improved by 10.4% from PRE to POST. Knee extension strength significantly improved 10.3% (p = .020) from PRE to POST but hip extension (12.2%, p = .061) and hip abduction (6.9%, p = .598) strength did not change. Knee extensors were the strongest muscle group (2.61 Nm·kg^{-1} [2.41, 2.82]), followed by hip extensors (1.78 Nm·kg^{-1} [1.58, 1.98]), and hip abductors (.86 Nm·kg^{-1} [.65, 1.06]) (all p < .001).

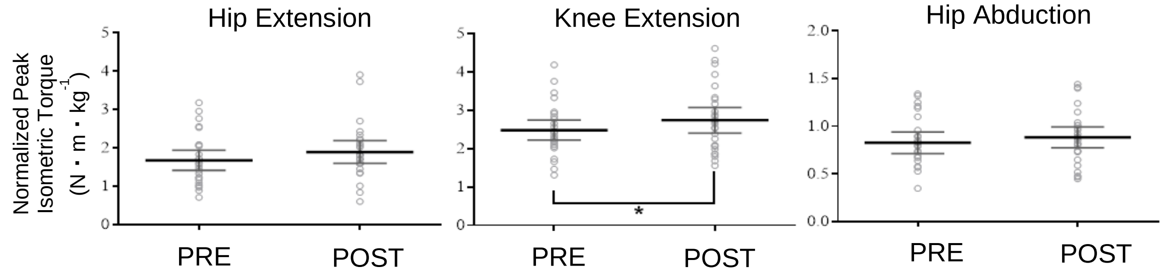

Figure 1: The normalized peak isometric torque for hip abduction, hip extension, and knee extension before (PRE) and after (POST) the six-week neuromuscular training program. Hollow circles: individual runners; thick bars: mean; whiskers: 95% confidence interval. *significantly different from PRE to POST, p < .05.

There was no effect of time on $\hat{k}_{vert}$ (F = 1.65, p = .213) suggesting that $\hat{k}_{vert}$ was similar at PRE and POST but there was an effect of time on $vGRF_{peak}$ (F = 4.51, p = .047). $vGRF_{peak}$ decreased 1.3% from PRE to POST. Further, there was no effect of time on cadence (F = 2.17, p = .154) or stride length (F = .130, p = .719) suggesting that cadence and stride length did not change from PRE to POST.

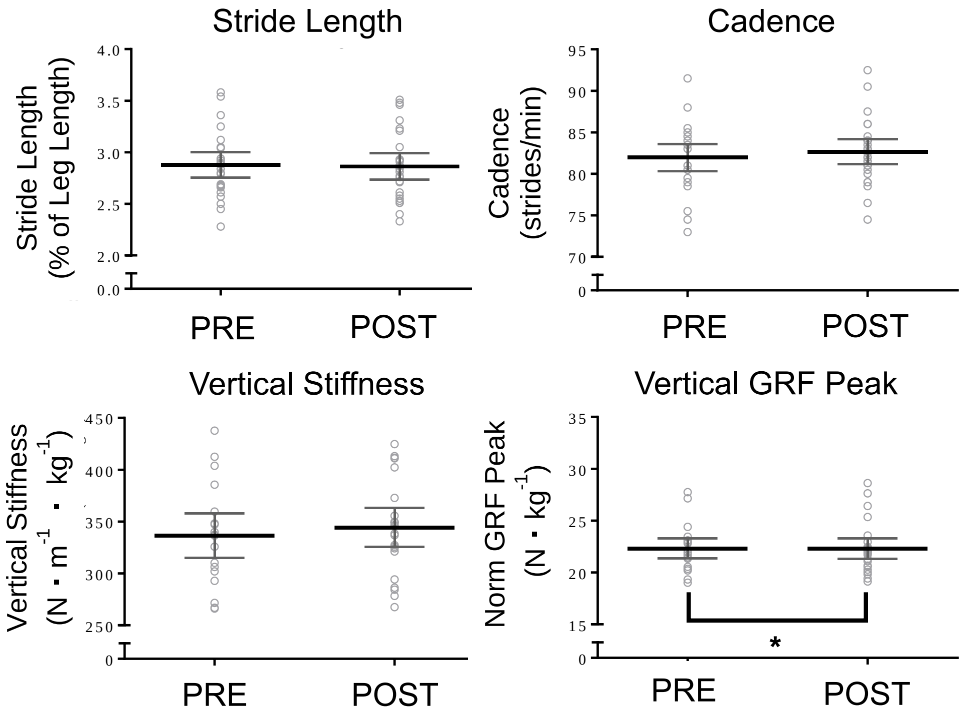

Figure 2: The normalized stride length, vertical stiffness, ground reaction force peak, and cadence before (PRE) and after (POST) the six-week neuromuscular training program. Hollow circles: individual runners; thick bars: mean; whiskers: 95% confidence interval. *significantly different from PRE to POST, p < .05.

Cadence (F = 85.2, p < .001) and running speed (F = 4.58, p = .043) were associated with $\hat{k}_{vert}$ suggesting that as cadence and running speed increases so did $\hat{k}_{vert}$. Stride length (F = 3.96, p = .057), hip abduction (F = .81, p = .380), hip extension (F = 2.52, p = .129), and knee extension strength (F = 2.15, p = .160) were not associated with $\hat{k}_{vert}$. Running velocity (F = 4.93, p = .036), stride length (F = 5.23, p = .30), and hip extension strength (F = 5.95, p = .024) were associated with $vGRF_{peak}$ suggesting that as running speed and stride length increased so did $vGRF_{peak}$ and has hip extension strength increased $vGRF_{peak}$ decreased. Cadence (F = .10, p = .752), hip abduction (F = .24, p = .630), and knee extension strength (F = 1.76, p = .200) were not associated with $vGRF_{peak}$.

Table 1. Fixed effects parameter estimates. *significantly associated with the dependent variable, p < .05.

	Dependent Variable	
Independent Variable	**Vertical Stiffness ($N{\cdot}m^{-1}{\cdot}kg^{-1}$)**	**Vertical GRF Peak ($N{\cdot}kg^{-1}$)**
Cadence ($strides{\cdot}min^{-1}$)	**8.96 [6.99, 10.92]***	**.02 [-.10, .14]**
Running Speed ($km{\cdot}hr^{-1}$)	**40.95 [1.37, 80.52]***	**2.49 [.17, 4.81]***
Stride Length (%LL)	**38.51 [-1.20, 78.21]**	**2.63 [.27, 4.98]***
Hip Abduction Strength ($N{\cdot}kg^{-1}$)	**-9.94 [-33.02, 13.13]**	**-.36 [-1.88, 1.16]**
Hip Extension Strength ($N{\cdot}kg^{-1}$)	**-5.62 [-13.04, 1.79]**	**-.58 [-1.07, -.08]***
Knee Extension Strength ($N{\cdot}kg^{-1}$)	**5.14 [-2.22, 12.51]**	**.31 [-.18, .80]**

DISCUSSION: The study showed that the NMT increased the runner's strength from PRE to POST, especially knee extensor strength, supporting the hypothesis. $\hat{k}_{vert}$, cadence, and stride length did not change while $v\widehat{GRF}_{peak}$ decreased, notably contrary to our hypothesis. Between-runners, $\hat{k}_{vert}$ increased with greater cadence and horizontal running speed, which is observed in sprinters compared to distance runners. $v\widehat{GRF}_{peak}$ increased with greater running speed and stride length and decreased with increased hip extensor strength. Thus, with decreased stride length, $v\widehat{GRF}_{peak}$ would decrease, potentially mitigating a risk factor for RRI. At constant speed, a decrease in stride length yields an increase in cadence. Therefore, it is inferred that an increase in cadence would show a similar decrease in $v\widehat{GRF}_{peak}$. However, as displayed in this study, an increase in cadence is associated with an increase in $\hat{k}_{vert}$, which can cause poor attenuation of repetitive forces, potentially increasing RRI risk. The overall effect of NMT on RRI risk is therefore difficult to predict, as there are two variables that, when altered, seem to have opposite effects on the biomechanical system. The apparent paradox described here demonstrates a lack of comprehensive understanding of the ramifications of altering healthy runners' biomechanics with the intent of preventing RRI and improving running performance, which warrants further study. This study also lacked a control group, therefore, the effect of six-weeks of a running program without NMT on strength and running biomechanics is unknown. In addition, the study used data averaged between both legs. It is possible that within a runner the NMT could affect the left and right or dominant and non-dominant leg disproportionately, although detection of this possible difference would require even higher fidelity data.

CONCLUSION: It is estimated that 28 to 40 million people in the United States run regularly and that 10 million people run more than two days per week. Prevention of RRI and improving running performance are common goals, and a NMT is frequently recommended as a complement to a running program to meet these goals. This study demonstrates the complex relationships between muscle strength and biomechanics. It highlights that there is a knowledge gap in preventative management for runners that requires further attention and study, and that clinicians should consider personalized treatment plans based on individual running mechanics.

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