The Effects of Varying Levels of Core Stability on Running Biomechanics and Compensations in Novice Runners

Undergraduate Research Thesis

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Abstract

Running is one of the most popular sports in the world. Because it is a very inexpensive sport to participate in, people from many demographics can become runners. Many runners suffer injuries each year. One factor that may impact a runner's risk of acquiring one of these running related injuries is their core stability. Based on the role of the core musculature, it has been hypothesized that less core stability may lead to inefficient movement and an increased risk for injury. Previous work determined that decreased core stability caused an increase in peak knee flexion moment which can lead to someone being more likely to have patellofemoral pain syndrome. A limitation to this study is that it was only experimental. As a result, information about muscle forces and the loads on the lower extremity joints were unable to be determined. The purpose of this study is to determine how neuromuscular and kinematic compensation strategies adopted in running when the core is fatigued impact the risk of injury. This was done by using data from the previously mentioned study and determining muscle force and lower extremity load data from simulations in the software OpenSim. The results of these simulations were that a kinematic compensation strategy increased the peak patellofemoral joint force and the risk for patellofemoral pain syndrome. Adopting a neuromuscular compensation strategy decreased peak knee abduction moment and impulse along with shear and compressive forces in lumbar vertebrae which decrease risk for patellofemoral pain syndrome and low back pain, respectively. Runners who are looking to avoid injury should implement core strengthening exercises into their training to increase the time before their core muscles begin to fatigue. This research helps reiterate the importance of core strength and its role in facilitating injury-free exercise for runners.

Introduction

Running is one of the most popular sports in the world. Because it is a very inexpensive sport to participate in, people from many demographics can become runners. Running has numerous health benefits including benefits in aerobic fitness and cardiovascular function [1]. The sport of running is not without risk, as around 50% of runners suffer an injury each year [2]. Along with painful symptoms, injuries can hold runners out from participating for a short period of time or even forcing them to abandon the sport completely. Three types of running injuries which are the most common are patellofemoral pain syndrome (PFPS), iliotibial band syndrome (ITBS), and tibial stress fractures (TSF) [3].

Patellofemoral pain syndrome presents as pain in the front or back of the patella bone at the knee. Previous studies have linked PFPS to several different biomechanical risk factors such as excessive knee abduction and hip internal rotation, and a greater peak hip rotation angle [3]. Iliotibial band syndrome can be felt as pain in the lateral part of the knee and along the lateral side of thigh up to the hip. Large hip adduction and knee rotation angles have been linked as risk factors for ITBS [4]. Tibial stress fractures are microfractures of the tibia bone and an increase in the vertical ground reaction forces during running has been associated with increased risk for a fracture [5].

Another type of running injury that both novice and experienced runners may endure is lower back pain. About ten percent of all running-related injuries are related to low back pain [6]. Like PFPS, ITBS, and tibial stress fractures, there are biomechanical indicators that may lead to someone being more susceptible to lower back pain. An increase in the compressive and shear loading of the lumbar vertebrae can lead someone to be more likely to experience low back pain [7].

One factor that may impact a runner's risk of acquiring one of these running related injuries is their core stability. Core stability is the body's ability to maintain or resume an equilibrium trunk and pelvis position following internal or external perturbations [8]. The core musculature of the body helps prepare the body for lower extremity movement and helps brace it against forces [9]. Based on the role of the core musculature, it has been hypothesized that less core stability may lead to inefficient movement and an increased risk for injury [10].

There is very little research that investigates how the body adapts running form if the core muscles are fatigued or not strong enough to be able to handle the loads put onto them. This is relevant for runners because when going on a run, the core muscles fatigue just like the muscles of the lower extremity fatigue and how the body adapts to this weakening may create a different environment than when the runner is not fatigued at the beginning of a run. Previous work has been done investigating how core stability impacts running kinematics by Chaudhari et. al [11]. Twenty-five novice runners had their overground kinematic data collected before and after completing a series of exercises meant to fatigue the core. They determined that decreased core stability caused an increase in peak knee flexion moment which can lead to someone being more likely to have PFPS. A limitation to this study is that it was only experimental and no simulations were run. As a result, information about muscle forces and the loads on the lower extremity joints were unable to be determined.

Determining the force of muscles and contact forces on joints is difficult to do experimentally and would be incredibly invasive. Computer models have been created that closely resemble the human skeleton that allow researchers to estimate these metrics. The software OpenSim is an open source biomechanical modeling software which allows researchers to complete simulations and obtain results that could not be acquired experimentally [12]. When

compared to actual measured joint forces in the body, OpenSim models produce similar but not exactly the same results [13]. OpenSim also allows for the changing of properties of individual muscles such as their maximum isometric force and length. This allows for researchers to directly study the effects of changing these variables while holding all others constant.

Previous work using simulations to study the impact of core fatigue on running was done by Dr. Margaret (Raabe) Van Horn at the Clinical, Functional, and Performance Biomechanics Laboratory at The Ohio State University. Raabe only conducted her simulations with eight of a possible twenty-five participants because she chose the inclusion criteria to be a 10% decrease in core stability and/or 10% increase in core muscle fatigue and a statistically significant change in one peak knee or hip variable previously associated with running injuries. Raabe used the Full-Body Lumbar Spine Model to complete her simulations, which is the first full-body OpenSim model to include muscle modeling of the core muscles [14]. From her eight-subject simulation study she concluded that a kinematic compensation strategy used during core fatigue increased knee loading and a neuromuscular compensation strategy decreased use of superficial core muscles but increased use of deep core muscles [15][16]. Raabe's pilot experiment made it plausible to expand upon it and investigate simulation results from all twenty-five participants from the original experimental dataset [11].

Following and extending Van Horn's pilot work, the goal of this experiment will be to determine the impact of both kinematic and neuromuscular compensation strategies on novice runners with any amount of core fatigue and determine how much these strategies are used as core fatigue increases. There are two main different types of compensation strategies that will be investigated in this study. First is a kinematic compensation strategy which is a modification of the actual kinematics and gait itself. The second is a neuromuscular compensation strategy where

the running form remains the same but the activations of muscles are allowed to change. Understanding how different compensation strategies present themselves as the result of a weak core can help clinicians spot gait patterns that can be corrected with core strengthening or neuromuscular re-education exercises to improve stability. These compensation strategies may lead to movement patterns that could make someone more at-risk for a common running injury such as PFPS, ITBS, TSF, or low back pain. If a patient is showing the signs of any of these injuries then strengthening the core could also be implemented into the rehabilitation plan as a potential way to lessen the risk of reacquiring these injuries.

This research will resolve how compensation strategies due to core fatigue impact novice runners. Understanding how runners compensate for core fatigue can help clinicians and runners themselves better understand their body and lead to changes in training methodology by increasing core exercises to prevent compensations and injury.

Methods

The data collected for these simulations was obtained from a previous experiment done by Margaret Raabe at The Ohio State University [11]. In this experiment, twenty-five novice runners had their three-dimensional overground jogging kinematics and kinetics collected before and after performing a core stability knockdown protocol that was developed to reduce core stability in single testing session [17]. Marker data were collected at 300Hz using 9 Vicon MX-F40 cameras (Vicon Motion Systems; Oxford, UK) and filtered using a 4^{th} order Butterworth filter at 15Hz. Ground reaction forces were recorded at 1500Hz from Bertec 4060-10 force plates (Bertec Corp; Columbus, OH, USA). Retro-reflective markers were placed on the upper and lower body using a modified point cluster technique and is shown in Figure 1 below [18]. Ten overground jogging trials were collected for each leg, both pre- and post-CSKP.

Electromyography (EMG) was used to monitor muscle activity during the CSKP. Electrodes were placed bilaterally on the external obliques (EO) and internal obliques (IO), and unilaterally on the dominant-side rectus abdominis (RA), and L5 lumbar extensor (L5) during the CSKP. Dual electrodes were used for the EO, RA and L5 muscles and two single electrode discs were used for the IO muscles [9]. Pre-gelled (Ag/AgCl), surface electrodes (A10011/A10005; Vermed, Inc; Bellows Falls, VT, USA) were placed as recommended by McGill to best reflect deep muscle activity [10] or directly on the most prominent aspect of the muscle belly and oriented parallel to the muscle fibers. Electrode locations were shaved, if necessary, and cleaned with alcohol pads. The median frequency (MedF) of the raw EMG signal for all core muscles was measured at the beginning and the end of the isometric exercises during the CSKP in order to obtain a measurement of core muscle fatigue induced by the CSKP.

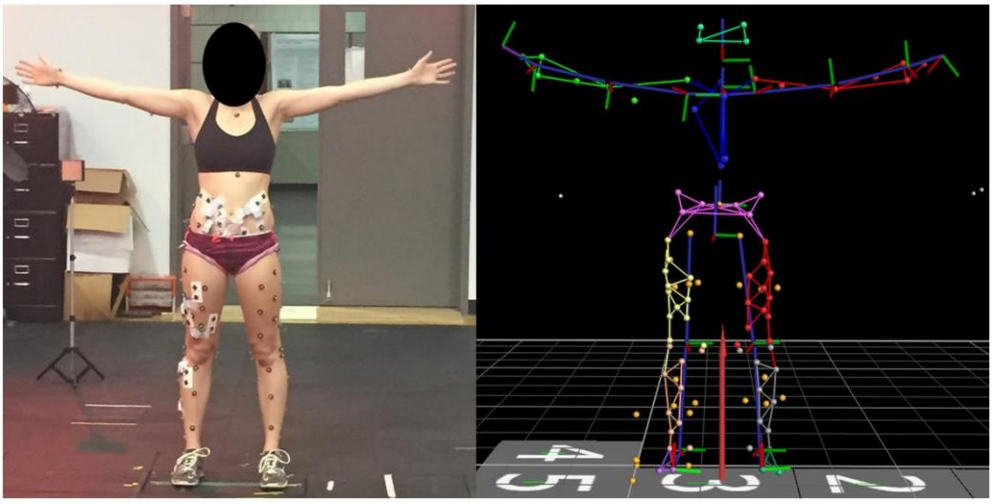

Figure 1: Marker set for experiment [16].

The start time of each simulation would be determined as the first time one of the feet was fully contacted by a force plate and it would end when the opposite foot was fully contacted by a force plate. If the simulation did not produce results that were within the acceptable thresholds on OpenSim's website for a successful simulation, the simulation would be rerun using the current end point as the new starting point and ending when the opposite foot was in

full contact with the force plate. An example of the start and stop points in a simulation is shown by Figure 2 below. This was repeated until there was a simulation in which the results were under the acceptable thresholds. The full-body lumbar spine (FBLS) model was used to create each simulation [14]. The FBLS model is freely available on the SimTK website (https://simtk.org/home/fullbodylumbar). The workflow used to create each simulation is shown in Figure 3 on the following page. First, the generic musculoskeletal model was scaled to anthropometrically match the individual participant for whom data had been collected [19]. Next, motion and mass properties of the model were optimized using inverse kinematics and residual reduction algorithms (https://simtkconfluence.stanford.edu:8443/display/OpenSim/Getting+Started+with+RRA) to achieve a dynamically consistent set of kinematics and kinetics that best matched the experimentally collected data [19, 20]. Next, static optimization (SO) was performed to resolve the net joint moments into individual muscle forces at each instant in time [19]. Non-physical forces and moments added to the model to resolve dynamic inconsistencies (residuals) or assist muscles that are too weak to produce the necessary joint moment (reserves) were compared to the established thresholds to ensure all simulations were successful [21]. Lastly, the JointReaction analysis tool was used to estimate the internal joint loads on the lumbar spine and lower extremities [21].

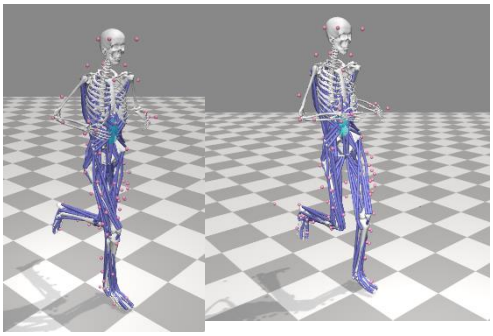

Figure 2: Start (left) and end (right) of a simulation.

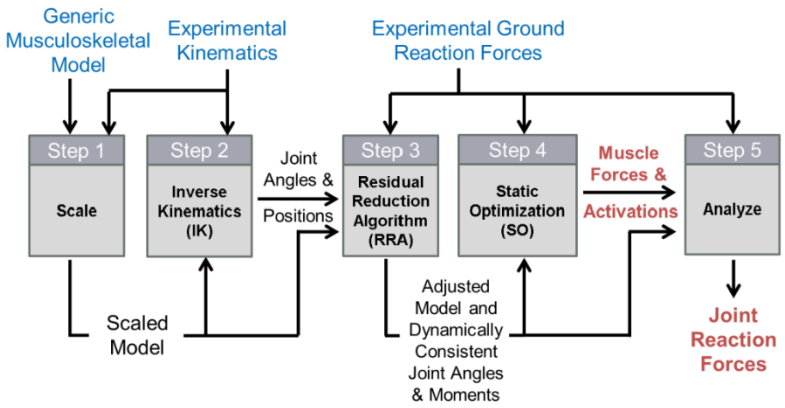

Figure 3: OpenSim workflow [19].

Four subject-specific simulations were developed for each participant and shown in Figure 4. A simulation with both pre and post kinematics with non-fatigued muscles was developed along with a muscle-fatigue simulation for both the pre and post kinematics. Muscle fatigue was accounted for in the model by reducing the maximum isometric force property of all trunk muscles in the model on a subject-by-subject basis based on the data acquired from the EMG used during the core stability knockdown procedure. Previously, this was done manually for each participant by editing the XML file that made up the FBLS model for each subject. A Python script was written that automated this process for each subject instead of having to manipulate and weaken each muscle fiber individually. The percent that the maximum isometric force was reduced for all core muscles was calculated using the following relationship: $\%\Delta MaxIsometricForce = \%\Delta AvgMedF * 2.57$, where %ΔAvgMedF is the percent change in the average median frequency of the core muscles as a result of the core stability knockdown protocol. The scaling factor of 2.57 was empirically determined by Raabe from published data and takes into account the relationship between the change in a muscle's force production and the corresponding change in its median frequency [16, 22].

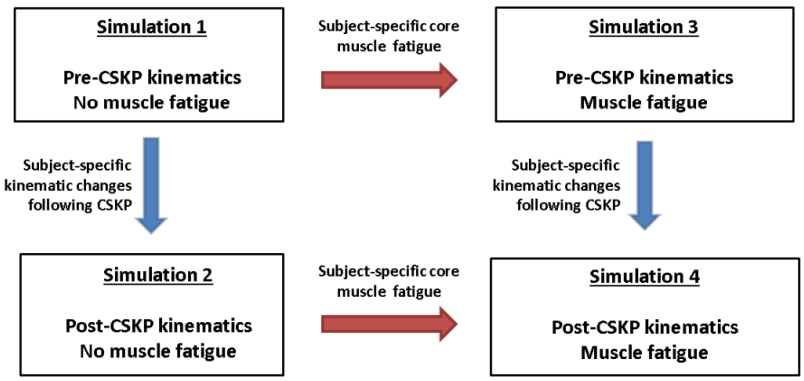

Figure 4: Four-subject specific simulations for each participant [16].

The variables investigated from these simulations were those associated with running injury risk. These variables included the peak axial load acting on the tibia, peak patellofemoral joint reaction force acting on the patella, internal peak knee abduction moment and impulse, internal peak knee extension moment, internal peak hip abduction moment and impulse, and peak and impulse of the anterior shear and axial compressive loads on each of the lumbar vertebra (L1-L5). Statistical analyses were performed in JMP® Pro, Version 17.0.0 (SAS Institute Inc., Cary, NC). Linear mixed models were used to evaluate the effect of simulated core muscle fatigue on the primary variables of interest in both the pre-CSKP kinematic state and the post-CSKP kinematic state. The kinematic state (pre-CSKP, post-CSKP), the core muscle fatigue state (none, fatigue), and the interaction between kinematic state and fatigue state were treated as fixed effects and participant was treated as a random effect.

Results

When adopting a kinematic compensation strategy and comparing subjects from pre to post kinematics, only one of the variables of interest showed statistical significance. The peak patellofemoral joint force acting on the patella increased significantly ($p<.015$) from pre to post kinematics. The average peak force was 11,662 N for the subjects using pre-kinematics and 12,393 N for the subjects using post kinematics. The increase in the patellofemoral joint force from pre to post kinematics can be seen in Figure 4 below.

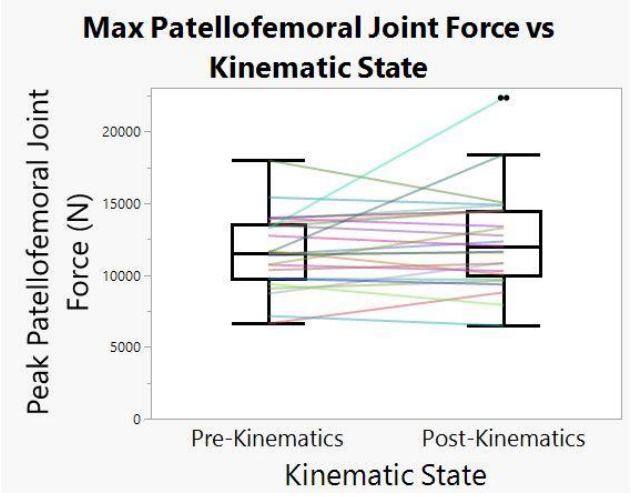

Figure 3: Max patellofemoral joint force based on kinematic state.

When adopting a neuromuscular compensation strategy and comparing subjects from their non-muscle fatigue state to their state with muscle fatigue, there was a significant change in peak knee abduction moment, peak knee abduction impulse, shear forces in the L1-L5 vertebrae, and compressive forces in the L1-L5 vertebrae. The peak knee abduction moment significantly decreased ($p<.0001$) from the non-weakened to weakened states. The average peak knee abduction moment for the non-weakened state was 1,324.9 N*m and 1,138.6 N*m for the weakened state. The peak knee abduction impulse also decreased significantly ($p<.0001$), with the average peak impulse for the non-weakened state being 248.7 N*s and 224.1 N*s for the

weakened state. Figures 5 and 6 below show these changes for both the peak knee abduction moment and impulse across core muscle fatigue state.

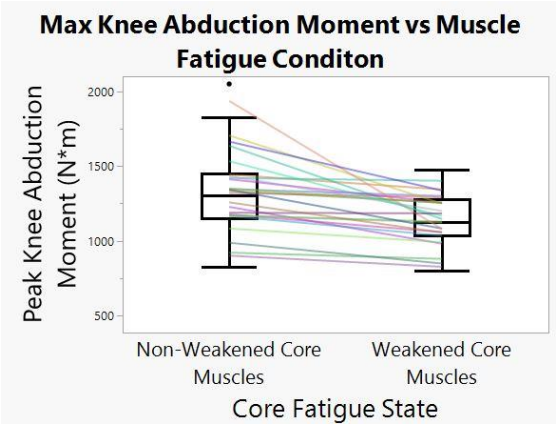

Figure 5: Max knee abduction moment by core fatigue state.

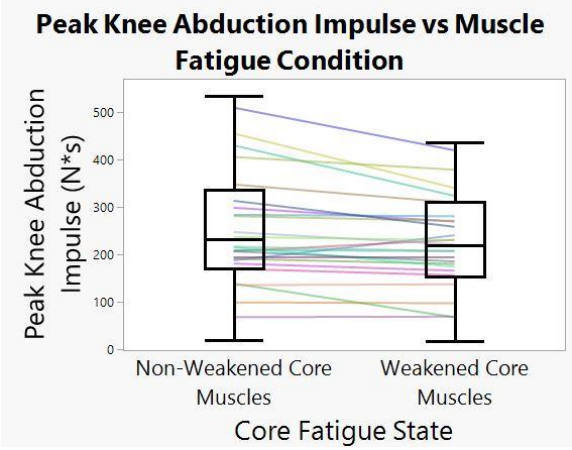

Figure 6: Max knee abduction impulse by core fatigue state.

There was also a significant ($p<.01$) decrease in both the axial and shear forces on all five lumbar vertebrae when going from the non-weakened to weakened states. Figures 7 and 8 on the following page summarizes the average compressive and shear forces for each of the five vertebrae for both muscle fatigue states.

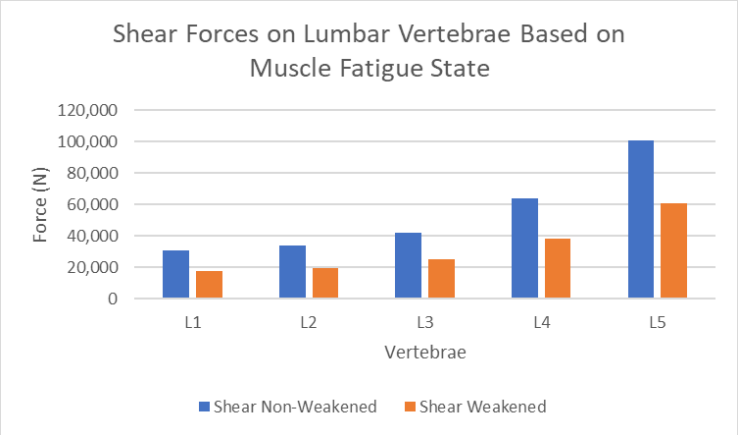

Figure 7: Summary of shear forces on lumbar vertebrae

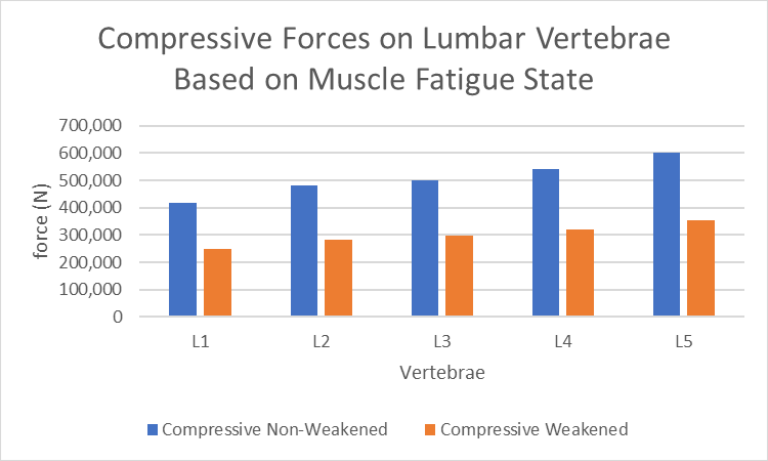

Figure 8: Summary of compressive forces on lumbar vertebrae.

None of the other variables of interest mentioned in the methods section had any statistical differences between either pre or post kinematics or non-weakened and weakened muscle states.

Discussion

When adopting a kinematic compensation strategy, the peak patellofemoral joint force increased. An increase in peak patellofemoral joint force has been linked to increase the risk for patellofemoral pain syndrome (PFPS) [16]. When adopting a neuromuscular compensation

strategy, the peak knee abduction moment and impulse decreased along with the compressive and shear forces of the lumbar vertebrae. A decrease in knee abduction moment and impulse has been cited to decrease the risk of patellofemoral pain syndrome [17]. A decrease in the compressive and shear forces of the lumbar vertebrae help reduce low back pain since these forces can be causes of low back pain [18]. A summary of all variables of interest and their significance is shown in Table 1 below. These results are similar to the results generated by the initial study done by Margaret Raabe previously. Raabe had additional variables of interest that were significant that this study did not find significant. Part of the reason this may be is because Raabe only included eight of the potential twenty-five subjects in her study because she only included those who had a 10% change or greater in core muscle strength or core muscle stability. This study included all twenty-five participants, including those who did not meet this 10% change threshold. The remaining seventeen subjects that were included in this studied showed less of a change in core stability and strength than the previous eight that were analyzed. Because they exhibited a smaller change, the adaptations they needed to make to compensate for their weaker core can plausibly be less drastic than the previous eight subjects. Because these adaptations are less drastic, it may have led to the entire population having less significant variables of interest than Raabe's previous study.

Table 1: Summary of variables of interest.

Variable of Interest	Neuromuscular Strategy	Kinematic Strategy
Peak Tibial Compressive Force	No Significant Change	No Significant Change
Peak Patellofemoral Joint Force	No Significant Change	INCREASE
Peak Knee Abduction Moment and Impulse	DECREASE	No Significant Change
Peak Hip Abduction and Impulse	No Significant Change	No Significant Change
Peak Knee Extension Moment	No Significant Change	No Significant Change
Lumbar Shear Forces	DECREASE	No Significant Change
Lumbar Compressive Forces	DECREASE	No Significant Change

The clinical significance of this work is that weakened core muscles can lead to a compensation strategy that can increase a novice runner's risk for injury. Runners who want to avoid potential injuries should include exercises that strengthen their core into their regular training regimen. When the muscle forces were examined from the non-weakened state to the weakened state, there was an increase in activation of the deep core muscles. This makes sense because the superficial core muscles were weakened in the simulation and other muscles needed to help compensate for that weakening. One important consideration is why weakening muscles in these simulations led to a decreased risk in injury. This weakened muscle state recruited more use of the deep core muscles which was most likely the cause of the decreased risk of injury, not necessarily the weakening itself. Given that the simulations ran successfully, this means that even with some muscles weakened, there was more than enough muscle capacity to accomplish the task and the act of reducing maximum force in superficial core muscles merely forced the simulations to use the deep core muscles more. If a compensation strategy is needed, a neuromuscular compensation strategy is preferred over a kinematic compensation strategy. This is because the kinematic compensation strategy led to an increase in the peak patellofemoral joint force, which increases the risk of PFPS. The neuromuscular compensation strategy decreased peak knee abduction moment and impulse which decrease the risk for PFPS along with decreasing the compressive and shear forces in the lumbar vertebrae. Novice runners should focus on maintaining their normal running form as much as possible to avoid a kinematic compensation strategy. Coaches and physical therapists can also help runners remember this as they fatigue later in runs or are rehabbing an injury.

Clinical significance of the changes in patellofemoral joint force is unknown. Future work could examine whether this increase is great enough to actually lead to an increased injury

incidence. Similar unknowns about the clinical significance of the decrease in lumbar shear and compressive forces appear and future work to determine if the decrease in these forces actually means a lower incidence of low back pain should be investigated. Future work to determine what percentage change increases or decreases injury incidence could be investigated for all of the variables of interest in the study. However, the simulation results from this study point to specifically investigating the patellofemoral joint force and the shear and compressive forces of the lumbar vertebrae since they were statistically significant in the study.

Future work that could be done to expand upon this experiment could be to include runners of all experience levels besides just novice runners. Novice runners are inherently new to the sport and may not have good form to start with nor will they necessarily know what their preferred running form is. As a result they may be changing their form a lot more than an experienced runner. Future work with more experienced runners will help give insight on if core strength is equally as important in preventing injury risk in all types of runners. Future work could also be done in investigating how the core fatigues during running and how that differs from the way core muscles fatigue as a result of the CSKP. The CSKP has been shown to reduce core muscle strength through its exercises, but we do not know if the level of fatigue is comparable to the fatigue the core experiences during a run. This work would give insight on if the CSKP is a good simulation of core fatigue that someone experiences during running or if a new protocol should be developed to better mimic what a runner experiences in their core during a run.

Some limitations of the study that may have influenced our results include that there are inherent limitations when running simulations. Simulations do not give the exact results, but rather a good estimate that we can draw conclusions from. Future work in this area will improve

as simulation software continues to improve to make simulations are comparable to collecting experimental data as possible. Another limitation of the study is that the data collection process did not necessarily mirror how a runner runs in the real world. In a real-world environment, a novice runner will be running outside and usually non-stop for potentially longer than an hour. In this experiment, the overground running trials were short and there were breaks in between the trials. This is mainly due to the confines of the Vicon camera system and it would be difficult to collect experimental data outside during a real world run because of this. It could be resolved however by collecting data from a treadmill instead of overground running so that the participant is running continuously and better simulating a fatiguing run.

Conclusion

The purpose of this study was to determine the impact of both kinematic and neuromuscular compensation strategies on novice runners with any amount of core fatigue and determine how much these strategies are used as core fatigue increases. The study was to expand upon the previous study done with only eight runners and expand it to all twenty-five participants in the study, including those who experienced less than a 10% change in core stability and/or core strength. The study concluded that when adopting a kinematic compensation strategy, the peak patellofemoral joint force increases which increases the risk for injury. When adopting a neuromuscular compensation strategy the peak knee abduction moment and impulse along with the compressive and shear forces of the lumbar vertebrae all decrease which all decrease the likelihood for injury in runners. Runners who are looking to avoid injury should implement core strengthening exercises into their training to increase the time before their core muscles begin to fatigue. When their core muscles do fatigue, implementing a neuromuscular compensation strategy is preferred to a kinematic compensation strategy. This research helps

reiterate the importance of core strength and its role in facilitating injury-free exercise for runners.

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