Limb Stiffness Increases with Hopping Frequency and Sprinting Speed in Elite Sprinters

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Abstract

During sprinting and hopping, the lower limbs act as a mechanical spring as it compresses and recoils to store and release elastic potential energy during each step. This is important because for individuals such as high performing sprinters, the stiffer the spring acting limb is, the more efficient it will be for the sprinter to maintain maximal velocity and optimal performance. The basis of this experiment lies in the fact that the mechanics of the lower limbs are modeled using the mechanics of a spring, therefore, to calculate an approximate limb stiffness, Hooke’s Law can be used. Hooke’s Law \(k=\frac{F}{\Delta L}\), where \(k\) is the spring constant, \(F\) is maximum ground force that is produce when the limb makes contact with the ground and \(\Delta L\) is the change in hip height between the middle of stance phase and initial contact. The purpose of this study is to investigate whether the knee or ankle contributes more to limb stiffness and the limb length change. The subjects of this study were 10 high performing track athletes that attended the University of Illinois. All subjects are asked to jump in place, on a force plate at 2, 3, and 4 Hz. Sprinting data were collected from a single ground contact near the end of a 60m sprint. All kinematic data such as the knee angle, ankle angle, and hip height was all captured using an optical motion capture system (Motion Analysis Corp.) and the reaction forces was recorded on an AMTI force plate. Data was analyzed using MATLAB and Microsoft Excel. Our results suggested that limb stiffness was dependent on the hopping frequencies, stiffness increases with the increasing in frequencies. With the addition of sprints, we also found that limb stiffness increases with increasing 1/Contact Time. At the same time, ankle and knee angles decrease with the increase in hopping frequencies, which is how stiffness is attained. However, for sprinting, knee and ankle angles increase. These results also suggest that dominant compliancy lies with the ankle.
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Introduction

For many athletes, form and technique is essential for maximal performance. Trainers and coaches spend months and sometimes years on sculpting their athletes to perfection. The study of limb stiffness is a perfect example of why. Take a sprinter, for example, as the runner gets out of the blocks and begins to reach maximum velocity, they’re body becomes more upright, their motions stiffen, and near-full extension of joints occur (Young. 2005). The study of sprinting mechanics proved to most important when it comes to sprinter training and the evolution of the sport. The spring model in Figure 1, serves as a basis of function of the legs and that information is used for training (Blickhan. 1989). Exercises such as jumping, and box jumps are common drills done sprinters that strengthen legs and joints so they can be most effective during a race, leg power informs the stiffness of a sprinter. (Chelly et al. 2001). For many years trainers and coaches have critiqued and molded their athletes into performing consistent sprinting techniques in efforts to improve the athlete’s performance. When a sprinter is in the phase of maximum velocity the joints in their lower extremities need to be compliant enough to absorb impacts and ensure smooth forward motion of the center of mass (Young. 2005).

Compliancy in joints is important for determining limb function. Through ankle and knee flexion during stance phase, the elastic potential energy is stored and released, creating the motion in a sprinter, and improving running economy. This study investigates which joint is most compliant that facilitates most to the overall limb stiffness. The most compliant joint, ankle,
or knee, is the one that deforms most, and may contribute to the compliancy of the rest of the limb thus, providing the most contribution to stiffening the runner’s limb (Bishop et al. 2006). Running at full speed and hopping are very similar motions when it comes to the mechanics, limbs stiffen up at the point of contact, enabling them to produce energy to spring upward/forward. The leg stiffness can be adjusted based on the speed and the obstacles that may come and it is the responsibility of the components in the limb to make those adjustments. There are many strategies that the leg uses to achieve limb stiffness and as mentioned before this study is investigating the strategy through joint compliancy (Farley et al. 1999).

In the spring-mass model, stiffness is measured using Hooke’s Law (Blickhan; Farley et al., 1999). The “springs” in a leg are composed of the complex system of muscles, joints, tendons, and tissues, all components that can regulate limb stiffness. However, the focus in this case is the ankle and knee joints. Using the equation $k=F/\Delta\lambda$ (Hooke’s Law), $k$ being the spring constant (measurement for stiffness), $F$ being the peak contact force, and $\Delta\lambda$ being the change in hip height from the initial point in ground contact and the mid stance. The source of these values came from the changes in knee angle during $\Delta\lambda$. As seen in Figure 1, the components of spring model and the leg are not much different, and the spring mass model explains the mechanism of bouncing very well.
Figure 1. Depicts the relationship and similarities between the spring-mass model and the model of the lower limb. As in a spring, the compression is due to the mass pressing down and the body of it compresses and stores energy to be released. In the limb, the body of the limb is compressed to the change in joint angles and the stiffening of the muscles.

**Literature Review**

“Sprinting should no longer be regarded as just a simple, natural activity. Full speed sprinting is a skill, which has to be learnt…” (Vonstein. 1996). After watching top class German sprinters, Vonstein (1996) mentions the upright posture, high-knee motions, and the full extension of lower limb joints. The main source of human speed is through powerful extension of the joints: ankle, knee, and hip. Vonstein concluded that the most influential joint out of the three was the hips because it displayed the most change in angle in the sprinting motion. The importance of these joints is stressed most when it comes to teaching technique and training, it is only when the sprinting motion is slowed and broke down, do we really realize this. For example, in drills like ankling, heel kicks, and high knee are taught to get in habits that would improve their techniques. For example, ankling, is a drill that teaches athletes how to properly lift and put down their foot while sprinting. It is a way to minimize the amount of time the foot spends on the ground and to minimize the power lost on contact. (Cissik. 2004). Teaching foot
action while sprinting is an emphasis on the use of the ankles, plantarflexion and dorsiflexion are essential. Farley et al. (1999) suggest that the stiffness of the limb mainly depends on the ankle stiffness and the study found that limb stiffness is adjusted changing the ankle torsional stiffness. Now, by reviewing both studies it can be concluded that the training that is being presented by Cissik plays a role in the performance of the ankle when in action. Training techniques such as ankling inform the importance of the ankle joint in limb stiffness. At the end of the day, all sprinting training techniques are methods of improving the efficiency of limb stiffness because it is what is responsible for the speed and performance of an individual.

Arampatzis et al. (1999) concluded that with the increase in sprinting velocity the stiffness of the knee and ankle joints increase, in addition, his study also suggested that the knee joint is more essential than the ankle joint in overall limb stiffness. This suggestion is agreeable considering the placement of the knee and the muscles and tendons connected to it. However, in a separate study conducted by Farley and Morgenroth (1999), the opposite is concluded, and limb stiffness is solely dependent on ankle stiffness. In this study, it was mentioned that there could be a variety of ways that can contribute to limb stiffness, the torsional stiffness or joints and the geometry of the musculoskeletal system was considered. In a system such as the lower limb, it was very hard to tell what specific strategy is responsible for stiffness, so it takes further experimentation to really figure out what strategy is used (Farley et al. 1999). Farley et al. conducted hop trials among their subjects to concluded that ankle stiffness was 1.5 times greater than that of knee stiffness. In this study, computer technology was used to observe the sensitivity of limbs stiffness which also observed the differences in ankle and knee stiffness.

All forms of human locomotion, involves kinematics, stiffness, and changes in joint angles no matter how fast. People often don’t realize that running and hopping are very similar
motions, hopping just doesn’t involve lateral movement. The lower limb exhibit spring like properties in both actions, running is essentially alternating leg hops. According to Cavagna et al (1971), running (alternating bouncing gaits) and hopping show similar properties in terms of limb stiffness, in fact, the frequency at which an individual may hop is equivalent if not greater than the stepping frequency in sprinting. However, the stiffness in limbs is a given because it is a mechanism that facilitates the storing and release of elastic potential energy, but when it comes to this research the joint at which facilities the stiffness the most is in question.

The goal of this study was to compare limb stiffness in hopping and sprinting, to evaluate how limb stiffness changes with both speed and hopping frequency, and to evaluate which limb joints are most compliant.

Methods:

At the start of the study, participants were explained the purpose of the study, their role in the study and risks and benefits of the study, the identities of the participants remain anonymous. Once their approval was obtained, 10 male NCAA Division 1 track athletes from the University of Illinois were interviewed for status on their general health, past health concerns, and status on their capabilities on completing physical activities. All trials were done inside an indoor track facility. Subjects were split into groups where they were asked to perform a variation of exercises and circuit training.

The data was collected by a sample size of 10 sprinters from the University track athletes. The athletes were asked to wear snug clothing to facilitate kinematic marker placement. Before collecting data, 27 lightweight markers (2cm diameter) were placed on the shoulders, arms, knees, hips, and feet. The anthropometric measurement of lower body components such as the thigh, skin and foot length were recorded. The markers were attached using doubled-sided
adhesion tape. The kinematic data was obtained using a 12-camera Motion Analysis at 240 Hz system (Motion Analysis corporation).

For each of the two sessions, the athletes were asked to perform repeated hopping exercises for six different frequencies in order. The athletes will have a metronome nearby to help keep the tempo in jumping. The following frequencies will be used: 2hz, 3Hz, & 4Hz. Like the previous exercise, athletes were asked to keep their hands at their side and the height at which they jump was regulated by a string that they have to touch. Height of the jumps will vary, and the joint flexions of the knees, hips, and ankle will be measured to see how stiffness varies with increasing frequencies. The hopping was done on an AMTI force platform to record the contact force. To minimize upper body movement and contribution to hops, subjects were asked to cross their arm across their chest.

In the subsequent part of the study, the athletes were asked to sprint to a short distance about 60 m and to strike a force plate mid sprint.
Figure 2. A picture that displays the placement of all the lower limb marks that would be capture by the optical motion cameras. That is what would give the results for ankle and knee. In the picture, the AMTI force plate can also be seen.

Certain trials had to be negated due to faulty data and missing markers. When the collected data from 2005, some of the data had to be cleaned because there were either misread or just misplaced in entirely (Figure 2). As a result, time needed to be taken to correct the data so it can read and interpreted. Once final clean data was produced, limb stiffness was calculated using Hooke’s Law (k=F/ΔL) because as mentioned, the limb is assumed to be a spring.

Using Excel, values from the Greater Trochanter (X, Y, Z), Knee (X, Y,Z), Ankle (X,Y,Z), Foot (X,Y,Z), Knee and Ankle Angle, Toe height and Hip height was cleaned and put into MATLAB, where more reasonable values could be found and results can be obtained.

A very similar process was undertaken for the sprinting data, faulty data was cleaned using Excel. Once cleaned, the same values were imputed into a separated Excel sheet, in which were transferred to MATLAB for more decipherable numbers were obtained. What gave us our final measurements was a premade Excel sheet, with equations that gave us measurements for stance duration, knee angle, ankle angle, stiffness, and force. Lastly, Excel was used once again
to make scatter plots that was able to compare the relationships of knee angle, ankle angle, stiffness, and force vs. stance duration for both hopping and sprinting trials.

Figure 3. The research data graph that would need addition attention and cleaning in order to be processed.

Figure 4. The research data graph after being cleaned. Clear hopping patterns can be seen and it ready to be further processed.
Results and Analysis

HOPPING

As seen in the Stiffness vs. Frequency graph (Figure 6), the limb stiffness has a direct relationship with frequency, meaning that as the frequency of the jumps increase, the stiffer the limbs get. These results suggest that limb stiffness is affected by hopping frequency, which makes sense if we compare it to the spring mass-model and the implications behind it. The data was collected at the midstance so this a point in time where energy is being stored and getting ready to be released. This point is similar to that of a running standpoint because the midstance of the sprinting motion is also when potential energy is stored to be released. As the frequency of the hop increases, the legs must stiffen more to facilitate the increase in speed. The point at which the limb contacts the ground is almost instant with the point as the leg stiffens, and energy is stored. In a similar study, it was found that limb stiffness is generally correlated with the maximal velocity (Chelly et al. 2017), which is the point in a race which the limb is generally in a “hopping” state.

In addition, as seen in the graph, the results start from 2 Hz, but as mentioned before the subjects were asked to start the hopping trials at a frequency of 1 Hz. This is because the results
from those trials did no exhibit spring like tendencies, which came as a surprise. Unfortunately, these results wouldn’t have been beneficial for calculating stiffness.

Figure 6. Stock plot of Stiffness vs. Frequency. Results of the study, as frequency increases, stiffness also increases, showing a direction relationship.

Using the optical Motion Analysis System, the results showed that both knee and ankle angels decreased as frequency increased. In figure 7, the trendlines showed a negative slope, showing an indirect relationship between ankle angle and frequency. As stiffness increases, the ankle angle is expected to decrease, so the storing of elastic potential energy is greatest when the ankle at its lowest during the whole trial. Now this study is supposed to be in comparison with the knee angle and the objective is to see which of the two joints are more compliant. Based on Figure 7 and Figure 8, we observe an indirect relationship and through the average changes in ankle and knee angle we observe compliancy in both joints. To determine which one is most complaint, we must look at the slope. The steeper the slope the more compliant the joint throughout trials.
Figure 7. Ankle Angle vs. Frequency Stock Plot. Indirect relationship details the ankle getting more compliant as the angles decrease.

Figure 8. Knee Angle vs. Frequency Stock Plot. Indirect relationship details the knee angles decreasing. Slope is less than the one of Figure 6.

SPRINTING

For the sprinting trials, all values were put in comparison with 1/Contact Time (x-axis). As seen in Figure 9, direct relationships can be seen between 1/Contact Time vs. Stiffness, Ankle Angle, Knee Angle, and Force. As 1/Contact Time increases, Stiffness, Ankle Angle, Knee Angle, and Force also increases.

Since hopping results were obtained a year prior, we were able to compare the two trials and analyze the relationships between the trendlines. For the comparison, Frequency was replaced by 1/Contact Time. As seen in Figure 9, the trendline for Stiffness shows a direct relationship, as 1/Contact Time increases, so does Stiffness. The same result goes for the
sprinting trials. In Figure 10, as 1/Contact Time increases, Ankle Angle decreases for the hopping trials. However, for the sprinting trials ankle angle decreases as 1/Contact time increases. As seen in Figure 11, Knee Angle trendline relationships are the same as in Figure 10. Lastly, in Figure 12, Force increases as 1/Contact Time increases, although, Force for the sprinting trials has a steeper slope.

Figure 9. Linear plot of Stiffness vs. 1/Contact Time for both hopping and sprinting trials. Represented by the trendline, stiffness for hopping and sprinting has a direct relationship.

Figure 10. Linear Plot of Ankle angle vs. 1/Contact Time for both movements. An indirect relationship is seen for hopping while an opposite direct relationship is seen for the sprinting trials.
Figure 11. Linear Plot of Knee Angle vs. 1/Contact Time for both movements. Same linear relationships are seen as in figure 4.

Figure 12. Linear plot of Force vs. 1/Contact Time for both movements. For hopping, the slope is very gentle indicating not much rate of change, however, sprinting experiences a steeper slope.

Conclusions and Implications

It is possible to draw the conclusion, based on the data and the studies that came before it, that those who run faster have limbs that are more rigid. While the knee and ankle angles reduced as the frequency rose, stiffness did. Surprisingly, there was no spring-like activity at the 1 Hz frequency, thus those findings were left out of the study. In other words, more of the energy produced by the muscles is held in the leg as elastic potential energy during the stance phase and subsequently released as kinetic energy. This could also be explained by the fact that with hopping at 1 Hz, there was too much time between hooping that spring like qualities of the leg
couldn’t be tested. As a result, 1 Hz trials were omitted in the second portion of the study. Higher leg stiffness enables for effective energy transfer during the ground contact phase. As a result of this elastic energy transfer, which lowers the amount of energy wasted as heat and increases efficiency, stiffer limbs are likely to move more quickly and perform better. With increased speed, the angles at the knee and the ankle contributed differently to stiffness; the ankle, being a mobile, loose adapter, had more angle flexion than the knee. Since the ankle has the most elastic energy storage capability, there was less stiffness there.

The study's sample size was lower than expected since a large portion of the data could not be adequately synthesized, and a large number of the reflective markers were misplaced or broke off. A larger sample size is advised for future replication in order to appropriately generalize the findings. The methodology and findings of this study were constrained by the small sample size. Future trials should also compare the spring kinematics of the sprinters to those of other athletes, such as distance runners and non-runners, in addition to including more participants than only NCAA D1 sprinters. Since sprinters must have elasticity storage for a longer period of time than distance runners, sprinters are frequently the focus of studies on running performance. Given the paucity of studies on the topic and the significant physical variations between the sexes, a comparison of male and female runners may be a future area of investigation.
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