Increased Shoe Bending Stiffness Increases Sprint Performance

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ABSTRACT

The purposes of this investigation were to determine if increasing the bending stiffness of sprint shoes increases sprinting performance and to determine whether simple anthropometric factors can be used to predict shoe bending stiffness for optimal performance. Thirty-four athletes were tested using four different shoe conditions — a standard condition consisting of their currently used footwear and three conditions where the bending stiffness was increased systematically. The sprinters performed maximal effort 40 m sprints and their sprint times were recorded from 20 to 40 m. On average, increasing the shoe bending stiffness increased sprint performance. The stiffness each athlete required for his or her maximal performance was subject specific but was not related to subject mass, height, shoe size or skill level. It is speculated that individual differences in the force-length and force-velocity relationships of the calf muscles may influence the appropriate shoe stiffness for each athlete to obtain their maximal performance.

Keywords: footwear, athletics, metatarsalphalangeal joint, midsole, anthropometrics, sport shoes

INTRODUCTION

Sprinting performance depends on a variety of factors that have been well documented (Wood, 1987; Mero et al., 1992). One of the critical factors affecting performance in sprinting is the ability of the sprinter to generate and absorb large amounts of mechanical energy during each ground contact (Fukunaga et al., 1978, 1981; Chapman and Caldwell, 1983; Ae et al., 1987). It has been shown that the energy absorbed and produced during ground contact is about the same at each of the ankle, knee and hip joints (Stefanyshyn and Nigg, 1997). However, unlike the other joints of the lower extremity, the energy absorbed at the metatarsalphalangeal (MP) joint is substantial while the energy produced in the second half of the stance phase at this joint is minimal. In sprinting, the MP joint bends as an athlete rolls onto the forefoot resulting in energy being

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absorbed in the shoe and foot structures. However, the shoe does not fully extend until after take-off. Thus, the absorbed energy, which averages about 48 J (Stefanyshyn and Nigg, 1997), is lost.

A similar phenomenon occurs in vertical jumping where the MP joint absorbs an average of 24 J (Stefanyshyn and Nigg, 1998). For vertical jumping, the lost energy could be decreased by increasing the bending stiffness of the shoe midsole (Stefanyshyn and Nigg, 2000). Furthermore, increasing the midsole bending stiffness led to an increase in vertical jump performance. Since the energy lost at the MP joint in sprinting is about twice as much as in vertical jumping, it was hypothesised that increasing the bending stiffness of sprint shoes could lead to similar results and improvements in sprinting performance.

Although it was expected that performance would be increased with increased bending stiffness, it was also hypothesised that different athletes would require different shoe stiffness for their maximal performance. Just as different individual characteristics such as mass, strength and skill level influence the necessary flexibility of vaulting poles (Ekevad and Lundberg, 1997; Linthorne, 2000) or the necessary dimensions of tennis racquets (Elliot, 1981) for maximal performance, it is foreseeable that sprint shoe stiffness needs to be tuned to individual characteristics to maximise sprinting performance. Individual differences in height, mass, foot length or skill level may influence the necessary shoe stiffness required by an athlete.

Based on the aforementioned hypotheses, the purposes of this investigation were:

1) to determine whether increasing the bending stiffness of sprint shoes increases sprinting performance and
2) to determine whether simple anthropometric factors can be used to predict shoe bending stiffness for optimal performance.

**METHODS**

Data were collected at three different locations and a total of 34 subjects participated in this investigation. Five subjects, two female and three male University of Calgary Dinosaurs Athletics team members were tested in Calgary, AB, Canada. Seventeen subjects, all male members of the University of Tennessee Volunteers Track and Field team were tested in Knoxville, TN, USA and 12 members of the Cuban National Athletics team, two female and ten male, were tested in Havana, Cuba. All subjects specialised in sprint, long jump, hurdle or decathlon events. Informed written consent in agreement with The University of Calgary Ethics Committee's policy was obtained from all subjects.

Four different shoe conditions were evaluated. One shoe condition, the standard condition, was each subject's own sprint spikes that they used in competition. The other three conditions consisted of different carbon fibre plates of varying stiffness (Figure 1) inserted into the standard shoes under the sock liner. The plates were approximately 1 mm thick and the same shape as the shoe sock liner, thus mimicking the interior shape of the sprint shoes. The bending
stiffness of the different plates, as determined by a three-point bending test, were 42, 90 and 120N.mm⁻¹. For all shoes, the same sock liners were used.

The data collected consisted of 20m sprint times. From a standing start, the subjects accelerated for 20m and then were timed from 20 to 40m using single-beam Brower timing lights placed at chest height. The resolution of the timing system was 0.01s. Subjects were required to complete a total of eight trials, two trials in each of the four different shoe conditions. The conditions were tested in random order with the subjects blind to the test conditions. For each shoe condition, the two trials were averaged to determine an average sprint time for the sprint shoe.

Prior to testing, a pilot study was performed with a single subject, an elite decathlete. He performed nine trials with his standard shoe. The times of the nine trials differed by a maximum of 0.02s with a standard deviation of 0.008s. From the pilot study, it was also determined that approximately eight or nine trials were the maximum number that could be collected before fatigue began to affect the results. Thus, the total number of trials that could be collected on four different shoe conditions was limited to two each.

All trials were performed on standard competition athletic tracks. During the trials, wind speed was measured using a wind gauge to ensure speeds were within allowable limits. All data collection sessions were performed under wind conditions between −1.0m.s⁻¹ and +1.0m.s⁻¹. As wind speed data were not
recorded for each individual trial, only verified to fall between ±1.0 m.s⁻¹, individual trials were not adjusted for wind speed. In addition to the sprint trials, each subject’s height, mass and shoe size was recorded.

To determine whether increased bending stiffness improved performance, sprint times between the different conditions were compared with a repeated measures ANOVA. Analysis was performed using SPSS 11.0 software. The level of significance was chosen as p < 0.10 because the consequences of incorrectly accepting a false result (slightly increased expenses for athletes and shoe manufacturers) are minor in comparison to the benefits of a positive effect (improved performance).

To determine the relationship between the sprinters’ anthropometric characteristics and optimal stiffness (the stiffness with which the athlete had their best average performance), least squares linear regression equations were fitted to the following sets of data: subject mass versus optimal stiffness, subject height versus optimal stiffness, subject shoe size versus optimal stiffness and sprint time (in the standard shoe) versus optimal stiffness.

RESULTS

Average sprint time for the 34 subjects was significantly (p = 0.07) reduced when wearing a sprint shoe with a plate stiffness of 42 N.mm⁻¹ inserted in the shoe in comparison to the standard shoes (Figure 2). On average, increasing the stiffness beyond 42 N.mm⁻¹ did not result in increased performance.

Individual differences existed between sprinters with some sprinters performing better with flexible plates and others performing better with stiff plates (Figure 3). The majority of subjects had their best performance when a plate

![Figure 2](image-url)  
**Figure 2** Average and standard error 20m sprint times for the four different shoe conditions tested. * indicates a significant difference from the standard condition.
stiffness of 42 N.mm\(^{-1}\) was inserted in the standard shoe (Table 1). However, there was a group of subjects that had their best performance in each of the different footwear conditions, including the standard shoe. The number of subjects in Table 1 is greater than the number of subjects tested because some individuals had equal best performances with more than one condition.

When considering the individual results, 29 subjects had an increase in
performance with at least one stiff plate condition in comparison to the standard shoes (Figure 4). Three subjects had a decrease in performance with all stiff plate conditions. Two subjects (subjects 13 and 28) had one stiff plate condition where they performed equally as well as they did with their standard condition. When comparing the best plate condition to the standard condition, sprint performance was significantly \((p < 0.001)\) increased by 1.2% across the thirty-four subjects (Figure 5).

**Table 1** The Number of Subjects who had their Best Sprinting Performance with each Shoe Stiffness.

<table>
<thead>
<tr>
<th>Stiffness [N/mm]</th>
<th>Number of Subjects</th>
</tr>
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<tbody>
<tr>
<td>Standard</td>
<td>5</td>
</tr>
<tr>
<td>42</td>
<td>18</td>
</tr>
<tr>
<td>90</td>
<td>8</td>
</tr>
<tr>
<td>120</td>
<td>7</td>
</tr>
</tbody>
</table>

**Figure 4** Maximal sprinting improvement with a stiff plate condition in comparison to the standard condition for each subject. Data are presented relative to the standard condition.

There was no relationship between any subject characteristics (mass, height and shoe size) and the shoe stiffness necessary for maximal sprinting performance (Figure 6). Similarly, there was no relationship between sprint time (skill level) and optimal shoe stiffness.
DISCUSSION

It has been suggested that double beam timing lights should be used for timing running events as the double beam configuration reduces the root mean square errors in comparison to a single beam system (Yeadon et al., 1999). Even with a single beam system in this study, the data were highly repeatable. Seventy percent of the 136 conditions tested (34 athletes x 4 shoes) had differences between the two repeat trials of 0.02 s or less. The data presented by Yeadon et al. (1999) were collected for a maximum running distance of 4.8 m but they did find that larger photocell separations lead to smaller errors in average speed. As a result, they recommend having the separation of the photocell beams as large as practically possible. It is likely that the large separation used in this study, 20 m, helped increase the repeatability of the measurements.

Wind speed can have a large influence on sprinting performance (Ward-Smith, 1985; Dapena and Feltner, 1987; Linthorne, 1994). In order to limit the influence of wind, only trials that were collected at wind speeds between +1.0 and −1.0 m·s⁻¹ were used in the analysis. Even within these tight constraints, differences in wind speed could still influence the results (Linthorne, 1994). However, since the different conditions were randomly distributed amongst the athletes, the wind influence should be randomly distributed as well.

The outcome of this study supports the hypothesis that increasing the bending stiffness of sprint shoes could lead to improvements in sprinting performance. There was a significant decrease in sprint times using stiff plates (42 N·mm⁻¹) placed inside sprint shoes. Hopkins et al. (1999) suggested that the smallest performance enhancement that is worthwhile for an athlete at an elite
Figure 6 Relationship between optimal shoe stiffness and subject mass, height, shoe size and sprint time. Optimal shoe stiffness is defined as the stiffness with which the athlete had their best average performance.
level is 0.4–0.7 of the within athlete variation in performance between events. For high-level sprinting, they found this variation to be about 0.9%. Thus, a performance improvement in sprinting of about 0.36 to 0.63% should make a difference in a sprinter’s chance of winning a particular race. The average difference between the standard shoes and the shoes with the stiff plates (42 N.mm$^{-1}$) was 0.69%. Thus, it is expected that the performance improvements measured with the stiff plates could result in actual performance improvements that will be realised during competition. Performance improvements of 0.7% are quite large in elite sprinting or long jumping and may mean the difference between finishing in the medals or not.

The results were similar to previous results that showed increased jumping performance with increased MP bending stiffness (Stefanyshyn and Nigg, 2000). In this previous study, it was theorised that the increase in jump performance was the result of a reduction in the energy lost at the MP joint. Although this could partially explain the current results, other factors must be involved. Based on the minimisation of energy loss concept (Nigg and Segesser, 1992), as shoe stiffness increases, the energy lost at the MP joint decreases and performance should increase. However, this was only found to be true as stiffness increased to a moderate value, after which average performance decreased and this relationship no longer held. Therefore, other factors must also be involved and it is speculated that certain parameters of the individual athletes could play a role.

The hypothesis that different athletes would require different shoe stiffness for their maximal performance was also supported. In fact, specific footwear configurations increased performance by over 2% for one-quarter of the athletes tested. Two trials per condition may not be enough to identify the optimal stiffness of a particular athlete. This would require a slightly different protocol with many trials per condition to limit the variability between the conditions. However, it was apparent from the data that the optimal stiffness differs between subjects and that this stiffness is independent of subject height, weight, and shoe size. Heavier or taller subjects do not necessarily require stiffer shoes than lighter or shorter subjects. The optimal stiffness was also not related to skill level as some of the fastest sprinters had their best performance with a very stiff shoe while others had their best performance with a flexible shoe. Thus, simple anthropometric measures were unable to predict optimal stiffness criteria and it may be that more complex variables, such as energy aspects, need to be analysed.

One limitation of this investigation was that the shoe stiffness of each subject’s standard shoe was not measured. Small differences in each athlete’s particular footwear may affect the results. For example, the subjects who had their best performance with their standard shoes may have had stiffer shoes to begin with. However, the bending stiffness of typical sprint shoes is quite low, approximately 5–10 N.mm$^{-1}$. Initial tests indicate that the bending stiffness of the standard shoes and the stiff plates are roughly additive. Thus typical sprint shoes are about 5–25 times more compliant than the test conditions. It is speculated that the possible errors due to the small differences between the standard shoes did not have a large influence on the results. Another limitation
is that the athletes were still accelerating when the data were collected. It is currently unknown how running at constant speed might affect the results.

One potential influence of changing the shoe bending stiffness is a change in the point of application of the ground reaction force. For example, increased bending stiffness may move the centre of pressure of the ground reaction force anteriorly. The result would be an increased lever arm and greater moments about the ankle joint that need to be counteracted by the ankle plantarflexors. If the calf muscles are strong enough to generate this additional force, the result should be an increase in performance. However, in a real life situation, there will be a limit to the force that these muscles can produce. As a result, the optimal stiffness may depend on individual force producing capabilities of the athlete. Furthermore, the changes in position of the ground reaction force could also result in changes in the joint angular velocities. Thus, the force-velocity relationship of the ankle plantarflexors could have an influence as the shift in angular velocity could move closer or further away from the velocity where the athlete has their peak power production.

It is apparent that individual tuning of the athlete's shoe stiffness to the athlete's particular characteristics is required to maximise performance, which relates to the concept of optimising the musculo-skeletal system (Nigg et al., 2000). However, it is currently unknown what individual characteristics dictate the appropriate shoe selection. It is speculated that the optimal equipment for each athlete is dependent upon their plantarflexor strength and their personal force-length and force-velocity characteristics. Thus, further data on the energetics of sprinting with a stiffened MP joint are required to fully understand how to appropriately tune the shoe stiffness to an individual athlete to maximise the athlete's performance.

CONCLUSION

The bending stiffness of sprint shoes appears to have an influence on sprint performance. Current sprint shoes may be too flexible for many athletes who could benefit from an increase in the bending stiffness of their shoes. However, increasing the stiffness too much may negate the benefits.

It is speculated that the specific characteristics such as the force-length and force-velocity properties of the calf muscles of individual athletes may be related to the shoe stiffness required for maximal performance. However, until these relationships are established in more detail, athletes and coaches are recommended to experiment with shoes of different stiffness for obtaining optimal performance.

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REFERENCES


