Comparison of Biomechanical Performances of FlatFree™ Amerityre and Traditional Pneumatic Bicycling Tire

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Abstract:

The biomechanical comparison of a closed cell polyurethane and a traditional pneumatic bicycle road tires were investigated. The study consisted of 4 amateur cyclists and one former professional cyclist who attend the University of Ottawa. The study compared a closed cell polyurethane tire (Flatfree™ Amerityre tires 700 C x 23mm, replicating ~97 psi) and a traditional pneumatic tire (Vredstein® Recorso tires 700 C x 23mm) on bicycle rollers. The force required to pedal with the two different tires was recorded through the use of Tekscan F-scan® Mobile piezo-electric insoles. It was determined that the total difference in force between the pneumatic tire and the Flatfree™ tires is not found statistically different since P-value > 0.05 for both the series of 10 second sprints and 20 minute endurance trials. This displays that under these conditions the closed cell polyurethane tire does not provide a significant difference in performance when compared to the traditional pneumatic tire.

Introduction:

The cycling industry has evolved many systems to combat tire puncture problems such as tire sealants and tubeless tire systems that promises to eliminate punctures of tires. These systems aid in certain scenarios to eliminate the need to carry the necessities to change/repair a flat tire (such as a replacement tube, patch kit, tire levers and a pump). The Flatfree™ tire from the Amerityre Corporation that has produced a solid polyurethane tire. It is comprised of a one piece closed cell polyurethane construction. A solid tire would have the distinct advantage over a pneumatic system by eliminating the worry of having to repair a punctured tube. The following study compares the biomechanical differences of a Flatfree™ road cycling tire (700 C x 23mm) and a traditional pneumatic clincher road tire (Vredstein® Recorso, 700 C x 23mm).

The study is comprised of 4 amateur cyclists and one former professional cyclist pedaling on cycling rollers while the forces exerted onto their insoles is recorded. This is performed by the use of a piezo-electric insoles from the Tekscan F-scan® Mobile system placed over the participant's cycling insoles. The participants used their own bicycles while tested so that a representation of the individual's biomechanical effects could be presented. The testing consisted of the participant pedaling the bicycle rollers with a fork mount to aid in stability and consistency as well as safety. Two main tests were performed: an endurance test and a sprint test. The endurance testing consisted of the participants pedaling two 20 minute trials (one on each tire). During these tests the subject chose their own cadence and gear ratio but had to remain constant through both conditions. Recordings with the F-scan® Mobile system was done every 5 minutes for 10 second intervals. The sprint testing was comprised of the participants performing an all out effort for four 10 seconds intervals with each tire. Again, the cadence and gear ratio had to be the consistent for this test to maintain a constant speed. By recording the applied forces the biomechanical differences between the two tires could be measured.

Review of Literature:

The production of cycling tires is a competitive industry with the predominant leaders in automobile tire manufacturing such as Michelin® and Continental®. The desire to produce a greater cost efficient method and user friendly product is not only lucrative in fiscal terms but it is also highly desired by the consumer. This possibility of producing a solid tire that has similar characteristic to a pneumatic clincher tire would eliminate the need for consumers to have the worry about the maintenance and repair involved with common pneumatic tires. When considering the manufacturing of tire design one must take into account such ideals as rolling resistance, spring constant, compression and durability (Gordon, J., Kauzrich, J. & Thacker, J., 1989). It is these elements that translate into the key aspects of bicycle tire handling and ride characteristics.

In a survey performed by Moritz it is estimated that the average bicycle commuter distance traveled each is 3100 km annually for a 5100 km total for all bicycle travel (1997). Since such a large amount of time is spent riding their bikes, these individuals tend to look for reliability, durability and comfort when shopping for their tires. Reliability is a key asset since the current pneumatic tire systems rely on a pneumatic bladder system that, when not protected enough or inflated properly, is prone to punctures. This renders the tire momentarily and perhaps permanently useless as well as creating an inconvenient situation. Generally, an individual needs to carry a spare tube, pump, patch kit and tire levers to repair a punctured tire. Therefore it is enticing to have an almost failsafe tire system. The only current solution appears to be a solid single unit tire that requires no bladder to give itself the necessary ride characteristics.

Tire Characteristics

The main concerns that tire manufacturers consider when testing new tire designs are rolling resistance, wear resistance, spring constant and static friction (Gordon et al., 1989). All these aspects will affect the velocity, handling and comfort level of the tires. The rolling resistance is one of the greatest concerns that are affected by the tread pattern, width, contact area, surface friction and the material of the tire. It is generally deduced that the smaller the surface contact area of the tire the lower the resultant rolling resistance (Moore, D., 1975). The amount of force needed to be applied to the pedals is strongly dependent on this rolling resistance. The wear resistance of the tire is essentially a measure of durability; however a softer material generally results in greater traction and increased friction. When considering solid tires, Morgan suggests that closed cell polyurethane tires have a greater life span when compared to rubber tires (1981). The spring constant is interchangeable with sidewall stiffness in terms of tires. The stiffer the tire sidewall or the higher the spring constant should equate to less deformation of the tire and a rougher more uncomfortable riding tire from the lack of impact absorption (Hull, M., Wang, E., & Moore, D., 1996). It is noted by Hays and Browne that tires need dampening to also increase their stability of the tire (1973). This increased stability also comes with the drawback of an increase in rolling resistance (Sawatzky, B. & Denison, I. 2006; Bohm, F., 1996). Static friction is not a major concern for cyclists since the amount of friction that in normal conditions is nominal and can be overcome with little force.

Tire Construction

There are three main materials used for solid tires which are polyisoprene (rubber), open cell polyurethane and closed cell polyurethane. Solid polyisoprene tires have the tendency to be heavy and have low rolling resistances but do not absorb impacts well; this results in an uncomfortable ride. Open cell polyurethane tires are similar to a sponge like construction. As the name implies it is comprised of open spaces that have the tendency to absorb moisture. They also lack durability and have a higher rolling resistance. Therefore, open cell polyurethane is a poor choice for tire construction. Finally, closed cell polyurethane tires are the most logical choice. The closed cell polyurethane tire is a network of closed cells that are manufactured to have a similar air pressure for each individual closed cell as observed in Figure 1. They generally have a low rolling resistance and are able to resist wear fairly well. Their higher spring constant than pneumatic tire has the tendency to generate a rougher ride than pneumatic tires. It is has been observed that these closed cell tires are manufactured in a variety of fashions in the automotive industry such as a liquid injection molded tire or cast tire that is similar in form to a traditional pneumatic (Morgan, J., 1981). These have a low rolling resistance but also a higher spring constant

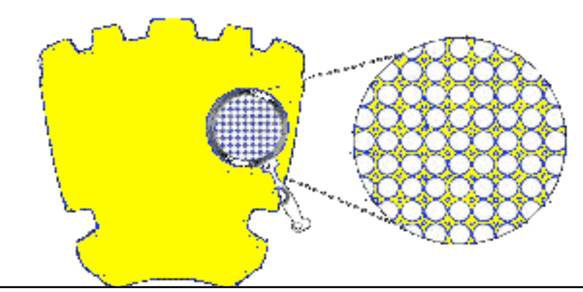

Figure 1. A cut-out of a Flatfree™ closed cell polyurethane tire (Amerityre Corporation, 2006).

than a pneumatic tire due to the stiff sidewalls which allow the tire to be driven without being inflated (Morgan, J., 1981). Also in the automotive industry, run-flat tires are simply a combination of a traditional polyisoprene (rubber) tire with a partial closed cell polyurethane or similar core which allow the user in case of an emergency to drive their vehicle while the tire is not inflated. The most promising innovation is the use of a solid tire that consists of a closed cell polyurethane spoke hub pattern with a solid polyurethane tread (Pajitas, S., 1990). These tires are close in the simulations to pneumatic tires while maintaining an acceptable spring constant (Pajitas, S., 1990).

There are two main types of pneumatic tire construction employed by manufacturers. The first construction method is called a diagonal ply or bias-ply tire. These are constructed of nylon or rayon cord that is laid at 40º angles to the centerline of the tire with the other layers placed in opposite directions and finally encased in rubber (Moore, D., 1975). The second tire construction is the common radial tire used in modern automobiles that are laid at 90 º angles to the centerline of the tire and embedded in a rubber carcass (Moore, D., 1975). It is found that radial tires generally have more desirable handling and ride characteristics due to its multidirectional layered structure which provides traction and side wall flexibility compared to the bias-ply tires (Moore, D., 1975). Cycling tires also have three main tire to rim interface combinations for attachment to the rim surface. The most common is the clincher system that has a wire bead that is built around the edge of the tire that fits under a lip built onto the rim. This system requires a tube and rim tape. Another similar system, introduced by Mavic®, is the Universal System for Tubeless (UST) tires which forgoes a tube and rim tape. A sealed area between the tire and rim is created to maintain tire pressure. The last cycling tire is of tubular styling which is the oldest method of tire to rim interface. This system employs a cloth or silk casing with a rubber tread that has a built in tube system (Kyle, C. & Burke, E., 1984). This tire is then glued to the rim surface. This system provides a lower rolling resistance and lower spring constant but is generally only used for road racing and track bicycles since the system is time consuming and difficult to apply (Kyle, C. & Burke, E., 1984; Kyle, C., 1988).

Testing Approaches

The most notable comparison between polyurethane tires and traditional pneumatic tires is the study performed by Gordon et al. on wheelchair tires (1989). The study employed method of testing the tires that relied on the use of a treadmill that had the tire attached to a support with a load cell attached to a cart with the tires mounted to it (Gordon et al., 1989). This allowed them to determine the rolling resistance of the tires as well as other tests determining tire spring constant, compression, impact absorption and wear. It was found that the pneumatic tire had the lowest rolling resistance of all four tires and had a lower spring constant. This supports the concept that pneumatic tires do provide a more comfortable ride than closed cell polyurethane tires (Gordon et al., 1989). It is displayed that the wear resistance of the closed cell polyurethane tire is close to that of the pneumatic tire (Gordon et al., 1989). As observed during the collection of research on cycling polyurethane tires there is a definite lacking in this area. Most of the research performed has been in the areas of automotive tire technology since it is lucrative in terms of profit margin to develop a closed cell polyurethane tire.

Methodology:

Participants:

The participants consisted of 1 female and 4 male students attending the University of Ottawa with ages ranging from 24-29 years. They are all amateur cyclists except one who is a former professional. They all provided their own bicycles and shoes for testing.

Table 1. Information of the 5 participants tested: gender, height, weight, age and cycling experience.

Participants	Sex	Height (m)	Weight (kg)	Age (yrs)	Cycling Experience
1	Male	1.75	68.4	24	Amateur
2	Male	1.85	79.5	24	Amateur
3	Female	1.62	52.3	27	Amateur
4	Male	1.8	70.4	26	Amateur
5	Male	1.7	68.9	29	Former Professional

Preparation:

1) The Sram PG 970 cassettes are installed on both Shimano Ultegra rear hubs and the pneumatic tire (Vredstein® Recorso 700 C x 23mm) is installed onto one wheel while the airless tire (Flatfree™ Amerityre® 700 C x 23mm) is installed onto the other wheel.
2) The pneumatic tire is then inflated to the corresponding values of the airless tires in this case ~97 psi.
3) The Vicon® markers can now be placed on the participant's bicycle after it is mounted on the rollers by referring to the diagram provided in the appendix.
4) The participant's Vicon® markers are then placed accordingly on their body by referring to the diagram provided in the appendix.

5) The F-scan® Mobile system's insoles are then trimmed and inserted over the insoles in the participant's cycling shoes.
6) The F-scan® Mobile system is then connected with the Vicon® system to provide synchronization of the two systems.
7) The F-scan® insoles are then calibrated to the participant

Testing:

1) The testing consisted of 4 stages in which the Vicon® and F-scan® data are captured for 10 seconds.
2) Test #1 (Pneumatic endurance) consists of the participant pedaling at a comfortable and consistent cadence and gear ratio for a total of 20 minutes with the pneumatic tire. The F-scan® and Vicon® data are collected every 5 minutes.
3) Test #2 (Pneumatic sprint) consists of the subject pedaling at a sprint intensity with a consistent cadence and gear ratio for a total of ~10 seconds with the pneumatic tire. The F-scan® and Vicon® data are recorded for 10 seconds when the subjects reached their desired cadence.
4) Test #3 (Flatfree™ sprint) consists of the subject pedaling at the same cadence and gear ratio to replicate the Pneumatic endurance Test #1 except utilizing the Flatfree™ tire instead of the pneumatic.
5) Test #4 (Flatfree™ endurance) consists of the subject pedaling at the same cadence and gear ratio to replicate the Pneumatic sprint Test #2 except utilizing the Flatfree™ tire instead of the pneumatic.

6) After testing the markers and the F-scan® system is removed from the subject and the bicycle.

*It shall be noted that the Vicon® markers are not crucial for this specific test but will be utilized for an alternate experiment. The cadence was determined by the participant's cycling computer's features or by the participant pedaling with a metronome.

Data Processing and Analysis:

To analyze the results of the study, the insole forces were recorded with piezo-electric insoles from the F-scan® Mobile system. The total force recorded for each foot of all trials was determined as well as the TAM areas which are the hallux, the 1st metatarsal head, the 2nd metatarsal head, the 3rd and 4th metatarsal heads combined, the 5th metatarsal head, the midfoot and the condyle of each foot. This data was then transferred into Microsoft Office Excel for statistical analysis in which the means were taken for all the trials and a Paired Sample T-test was then performed.

Results and Discussion:

It is noted that the mean cadence for the endurance trials was 80.8 rpm with a standard deviation of 1.79 rpm and a cadence of 148.8 rpm with a standard deviation of 15.8 rpm was recorded for the sprint trials.

It was observed in Tables 2 and 3 that $p > 0.05$ for all the total calculated force of the recordings. This means no significant difference between the two types of tire tested. However a difference (Fig. 2), although not significant, was observed when comparing the endurance trials (around 0.5%) when $p = 0.36$ and the sprint trials (around 2,5%) when $p = 0.168$.

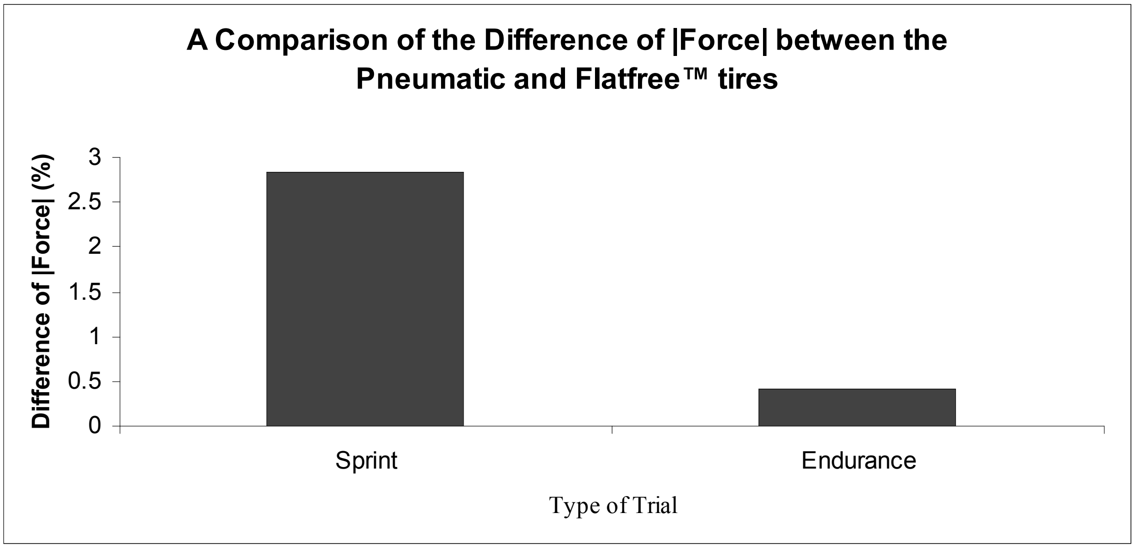

Figure 2. The absolute difference of the total force between comparing the pneumatic and Flatfree™ tires during the sprint trials (0.0283) and endurance (0.00415) trials.

Table 2. The Test values and *P*-values of the mean insole force of both insoles, left insole only and right insole only between the pneumatic sprint trials and the Flatfree™ sprint trials for 5 participants.

Insole	Test value (N)	*P*-value
Both	-1.033	0.36
Left	-0.368	0.73
Right	-1.121	0.32

Table 3. The Test values and *P*-values of the mean insole force of both insoles, left insole only and right insole only between the pneumatic endurance trials and the Flatfree™ endurance trials for 4 participants.

Insole	Test value (N)	*P*-value
Both	-1.809	0.16
Left	2.216	0.11
Right	-3.065	0.05

In Figure 3, the pneumatic tires required 652 N to remain at the same gear ratio and velocity during the endurance trials, while the Flatfree™ tires required 654 N. This suggests that the coefficient of friction is similar in their values. In Figure 4, the pneumatic tires required 675 N to remain at a similar gear ratio and velocity during the sprint trials, while the Flatfree™ tires required 695 N. This difference is not found to be significant for the sprinting trials since $t(4) = -1.809$, $p > 0.05$. The difference observed suggests that an increase in force may be required to counteract the increase in surface contact area and a resultant increase in rolling resistance during sprinting. This observed increase in deformation may have been the result of the subjects standing on the pedals while sprinting (instead of sitting during the endurance trials). Ideally during cycling the pelvis should remain stable to allow maximum efficiency (Burke, E., R., 1986). Four of the participants were amateur cyclists therefore increasing the natural rhythmic rocking that an individual may perform under power. This rocking may have produced a bouncing motion of the wheel thus deforming the pneumatic tire greater than the solid closed cell polyurethane tire and increasing its rolling resistance (Hays et al. 1973). It was also speculated with the use of the Vicon™ system that the former professional cyclist maintained greater stability and less bounce on the bicycle when compared to the 4 amateur cyclists. The characteristics of a solid tire suggests an increased spring constant to that of a pneumatic tire that does not allow the tire to absorb impacts as well and provides a less comfortable ride. This logically may have been the cause of the increase in the difference between the sprint trials and the endurance trials.

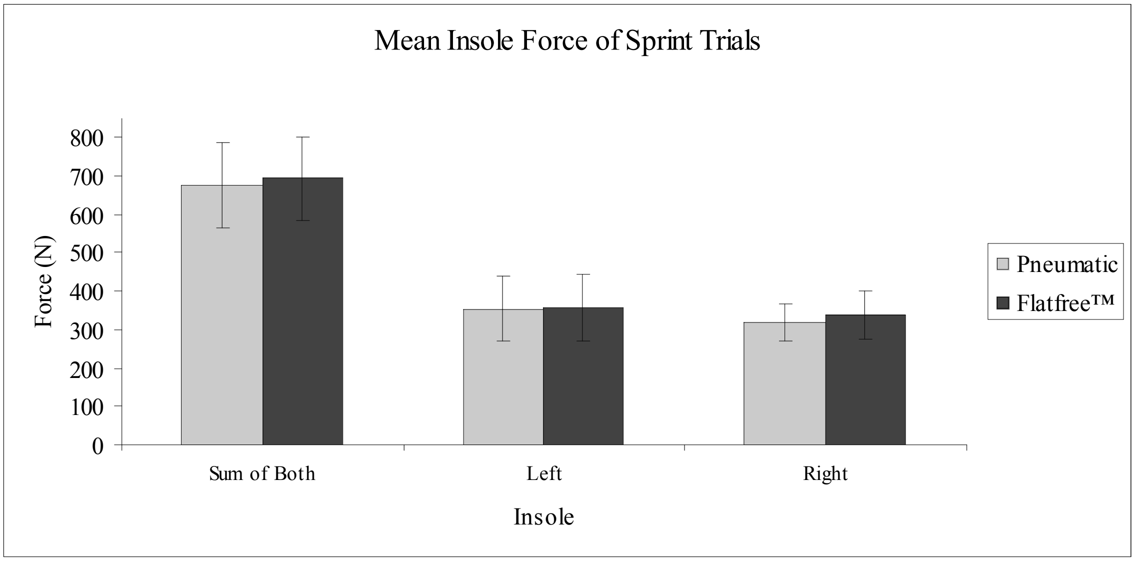

Figure 3. The total mean (±SE) of force for both insoles (left + right), the left insole and the right insole for the pneumatic and Flatfree™ trials for the 10 second sprint trials.

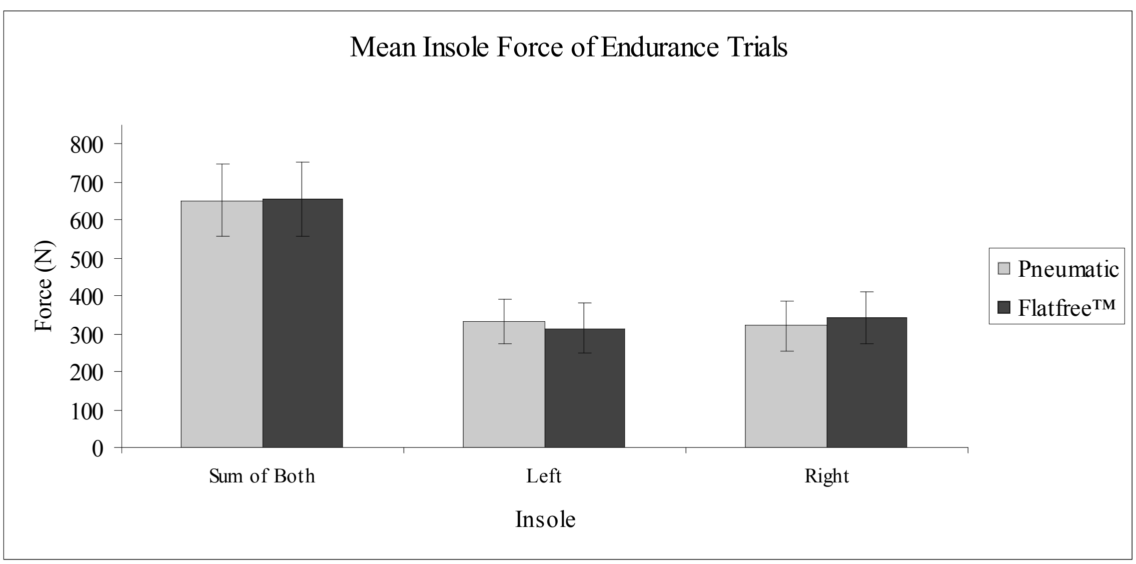

Figure 4. The total mean (±SE) of force for both insoles (left + right), the left insole and the right insole for the pneumatic and Flatfree™ trials for the 20 minute endurance trials.

It is also observed in Tables 4 and 5 that $p > 0.05$ for all the individual TAM box areas. This suggests that there is no significant difference of the force applied of the various areas of the foot in relation to the two different tires. It can also be noted that the hallux area produced the greatest amount of mean force (85.4 N) while the condyle area produced the second greatest amount of mean force (70.6 N) and the 5th metatarsal area producing the least amount of mean force (27.5 N) for the testing.

Table 4. The Test values and *P*-values of pneumatic vs. Flatfree™ tires in relation to the mean force of the TAM box insole areas of the hallux, 1st metatarsal head, 2nd metatarsal head 3rd-4th metatarsal head, 5th metatarsal head, midfoot and condyle are displayed for the sprint trials.

TAM Box	Test value (N)	*P*-value
Hallux	-0.698	0.524
1st Metatarsal Head	-1.77	0.152
2nd Metatarsal Head	-1.03	0.36
3rd-4th Metatarsal Head	0.126	0.906
5th Metatarsal Head	0.278	0.795

Table 5. The Test values and *P*-values of pneumatic vs. Flatfree™ tires in relation to the mean force of the TAM box insole areas of the hallux, 1st metatarsal head, 2nd metatarsal head 3rd-4th metatarsal head, 5th metatarsal head, midfoot and condyle are displayed for the endurance trials.

TAM Box	Test value (N)	*P*-value
Hallux	-0.66	0.557
1st Metatarsal Head	1.55	0.22
2nd Metatarsal Head	3.03	0.056
3rd-4th Metatarsal Head	2.14	0.122
5th Metatarsal Head	-1.23	0.307

When comparing Figures 5 and 6, it is suggested that the force is spread out over the foot more evenly during the endurance trials than in the sprint trials. This suggests that when cyclists stand for sprinting, the insole force has the tendency to be applied on the hallux and the condyle of the foot rather than spreading out more evenly over the foot. This conflicts with a previous cycling study performed by Hennig & Sanderson (1995) that the force exerted on the piezo-electric insole during cycling did not increase in the aforementioned method. It was suggested that the force distribution of the foot during the pedal stroke is increased through a greater applied force in the hallux and metatarsal area of the foot instead of the hallux and condyle that was observed in this study (Hennig et al., 1995).

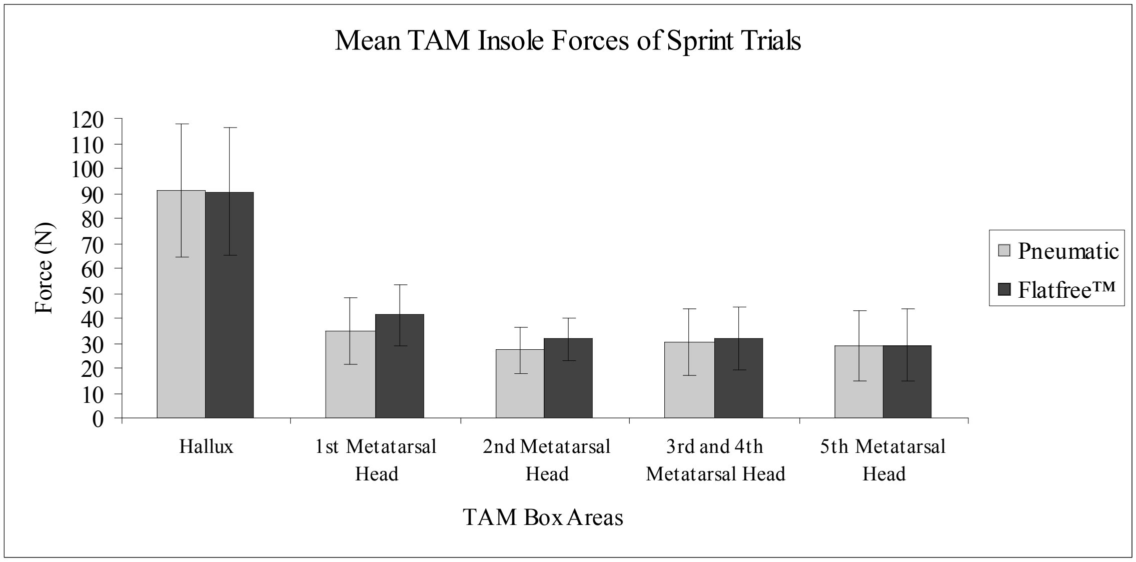

Figure 5. The mean forces (±SE) of both insoles utilizing the TAM box areas of the F-scan® program are displayed for the pneumatic and Flatfree™ tires during the 10 second sprint trials.

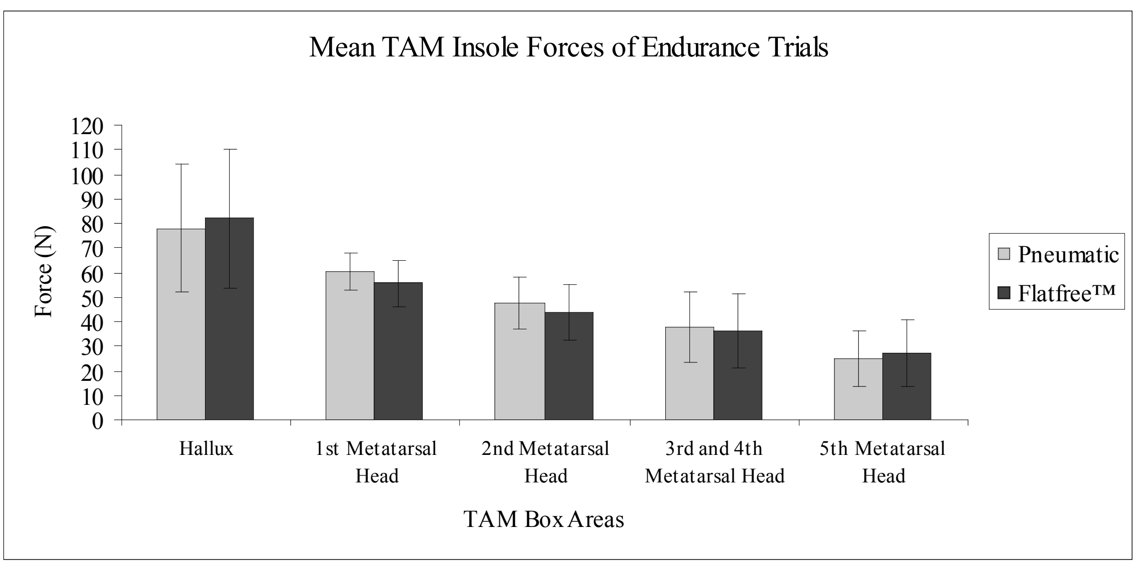

Figure 6. The mean forces (±SE) of both insoles utilizing the TAM box areas of the F-scan® program are displayed for the pneumatic and Flatfree™ tires during the 20 minute endurance trials.

The differences found during the analysis may be attributed to some sources of error during testing. It is possible that a participant may have not pedaled a consistent cadence during their endurance and/or sprint trials therefore affecting their velocities. This source of error is possible as two of the participants used a metronome instead of cycling cadence sensor. The participants may find the cycling cadence sensor easier to use and maintain a constant cadence than the metronome. Another source of error could be that between testing participant's pneumatic tires had to be re-inflated to a pressure of ~97 psi. This may lead to a difference between the participants relying on the accuracy of the floor pump. It is believed that a 25% decrease in rated inflation would produce an increase in rolling resistance of 10% so it is not likely that the air pressure was en enormous source of error (Gordon et al., 1989).

Conclusion:

In conclusion, it was found that there was no significant difference between the Flatfree™ closed cell polyurethane 700 C x 23mm tire and the Vredstein® Recorso 700 C x 23mm tires in either of the 20 minute endurance test trials and the 10 second sprinting trials. Therefore no significant biomechanical differences were observed in the comparison of a traditional pneumatic tire and the Flatfree™ tire on bicycle rollers. Although the closed cell polyurethane tires performed admirably, however the participants subjectively commented that they felt more resistance with the Flatfree tire than traditional pneumatic tire. Further investigations need to be performed for the tires under various other conditions.

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