Shoe Soles: An Application for Non-Newtonian Fluids

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Received September 13, 2024
Accepted May 05, 2025
Electronic access May 31, 2025

Non-Newtonian fluids are investigated as a type of smart material suitable for shoe soles. The different levels of support and comfort in different instances made it hard for traditional shoes to maintain both of them at all times. This paper studies the best concentration of non-newtonian fluid as a material for shoe soles, and how shoe soles can be manufactured using non-newtonian fluid to increase the comfort of the shoes. An equation is derived from the viscoelastic model and Newtons second law, which is able to process measurements to allow us to compare different fluid properties.
Experiments were run to test the Ground Reaction Force (GRF) of each step taken, to find a non-Newtonian fluid which will turn soft and hard at the specific GRF point. After matching the suitable fluid, there is a visualization of how this differs from normal shoe soles. The effect of the shoe soles will be presented in GRF values for given viscosities and the results show that it can be very viable using non-newtonian fluid as a material of shoe soles if the correct material is selected. At last, specified arrangements of concentrations in different parts of the shoe sole are exemplified and explained.
Keywords: Non-Newtonian fluid, STF, Viscoelastic model, GRF, Oobleck, Shoe soles, Sports equipment

Introduction

The choice of material is crucial as it allows a product to perform as expected under different situations and, in some cases, achieve additional functions. For example, iPhones use ceramic shields instead of normal plastics as their touchscreens which allows phones to perform well under most situations they face daily, such as being touched by all kinds of objects, especially fingernails.

Other products also require the material to change in different circumstances to operate the expected function. This can be complicated as normal materials are often good in certain situations, but considered as bad or unsuitable in other systems. However, some materials, often labeled as smart materials, respond to different environments and can be considered suitable in more complicated systems. Therefore, choosing the right material and adjusting the properties to suit the needs of a product is very important.

Non-Newtonian fluid is a category of fluids that exhibit responses to a change in shear stress, commonly seen as the change in pressure in application. With the change of force applied to non-Newtonian fluids, their viscosity changes with the force. This is due to the mixture of substances of different sizes contained in non-Newtonian fluids.

Large molecules will form clusters under an applied force and the clusters will pile over each other, forming a structure that will stop the flow to some extent. From a macroscopic view, this allows non-Newtonian fluids to exhibit a higher viscosity when a force is suddenly applied to it. This is the mechanics and performance of a particular type of non-Newtonian fluid called Shear Thickening Fluid. This characteristic is described by the word dilatant in fluid dynamics.

After obtaining data for these properties, a pair of shoe soles can be created that perfectly suits the need for support and comfort as the different forces are transferred to the soles. Fluids often provide a wider range of compression, property change, and other characteristics than solids as the particles are farther apart, so they can change more easily. Non-Newtonian fluids can adapt to the forces applied to them, improving on some additional characteristics as well, which makes it a suitable material for shoe soles.

The footware market industry was valued at 386.73 billion US dollars in 2023, and had grown to 404.13 billion in 2024. Specifically, the market size of the comfort footware market was 26.35 billion in 2023, which was around 6.81% of the whole footware market size in 2023. These data are supported by the market analysis Footwear Market Size, Share, and Growth Analysis [1] and Footwear market: Consumers desire comfort over appearance [2]. There is a huge amount a financial support in this field of research and it is reasonable to consider the improvement in shoe comfortability if non-Newtonian fluids are implemented.

However, the durability of non-Newtonian fluids is not satisfying as most of them are organic compounds. This is a very significant disadvantage of a shoe sole, which is required to last for long timescales. Therefore, various other perspectives on non-Newtonian fluids such as cost, chemical durability, and environmental damage should be considered. Comparing these to current shoe soles can help to identify if non-Newtonian fluids are a better choice to be part of the shoe soles.

There will be three sections of research to answer the question, each of them will examine an important part of the expected shoes and show how it is suitable.

Non-Newtonian fluid shows a different viscosity under different applied forces, which allows the shoe soles to exhibit a different hardness while people are applying different forces to them during different activities. When forces are applied to the shoes, more ground reaction force is required for support, which is what non-Newtonian fluids do. How it changes to fit the comfort zone will be important.

The balance between comfort and support for a pair of shoes is also important. As a pair of shoes, its purpose is to protect feet and give support, but it also needs to be comfortable for people to wear for a long time. This paper will deal with how the sole will be structured, both layers and the hardness of different parts. Additionally, how much ground reaction force is suitable for legs and feet is investigated to determine how hard the soles should be.

To be a useful sole, it is also important to perform well in other areas such as chemical durability, cost, and other important factors. This part will compare general shoes to this newly designed one to observe the advantages and disadvantages and determine whether non-Newtonian is good for producing shoe soles.

Method

An equation is derived to calculate the GRF from the experiment data and the viscosity of the fluid used. A walking test is performed to obtain data that is required for the formula. The GRF will be compared with the viscosity to find a concentration that theoretically has a better performance.

The first part of the research is to find an equation that connects the ground reaction force with the force of weight that is applied. It is found that how a high-speed object is decelerated by a non-Newtonian fluid is very similar to the kinetic energy loss modeled by the Viscoelastic model.

A study by de Goede[3]reviewed one of the most well-known models that describe viscoelasticity: the Maxwell model, which approximates the vicious and elastic responses of a viscoelastic fluid using a damper and spring connected in series. In this model, it is assumed that both viscosity and elasticity are independent of the magnitude of the introduced stress, and they are uncorrelated. For non-Newtonian fluid, the system is overdamped, and the viscous dissipation of the damper dominates. The formula Eq.1 is a function where the velocity V(t) decays exponentially over time.

$$v(t) = v_0 e^{-\gamma t} \tag{1}$$

where:

$$\gamma \equiv \frac{\eta}{2m_b} \tag{2}$$

In Eq.1, v_0 is the initial velocity of the impacting object. t is the time from the start of the impacting force is applied. This equation allows us to obtain the velocity of the impacting object which changes with time simply by the dynamic viscosity, initial velocity, and the shear stress. Substituting , the gamma symbol that represents the variable of shear stress, using variables for velocity and weight allows us to obtain Eq.3:

$$v(t) = v_0 e^{-\frac{\eta}{2m_b}t} \tag{3}$$

In Eq.3, the variable η represents viscosity of the fluid and m represents the weight of the impacting object. To calculate force using this formula, the velocity under the change of the variable t, time, Eq.3 is substituted into the equation for Newtons Second Law, F = ma.

In this example, F is the force we are applying while we are walking or running, while m is the mass of the walking person. a represents the acceleration of the velocity of our feet from the highest point to the ground, which can also be written as $\frac{dv}{dt}$, which is $\frac{V_0 - Vt}{t}$. This is where V(t) can be substituted as the viscoelastic formula we have, which allows us to calculate the force we applied to the shoe soles through Eq.4.

$$F = \frac{v_0\left(1 - e^{-\frac{\eta}{2m_b}t}\right)m}{t} \tag{4}$$

EqGRF equation describes the ground reaction force, which is the force that is given back to objects when they interact with the ground. Divide Eq.4, which is the force from the fluid, by the force from humans, mg, will provide a GRF equation. This allows us to calculate the different reacting forces we get from different walking speeds.

$$\mathrm{GRF} = \frac{v_0\left(1 - e^{-\frac{\eta}{2m_b}t}\right)m}{tmg} \tag{5}$$

In the contect of this experiment, the variables in Eq.5 rapresents the following. V_0 is the initial velocity of the feet of each step, η the viscosity of the fluid we use for the shoe soles, m the mass of people wearing the shoes, and t the time needed for feet to accelerate. These variables will calculate the GRF with our walking data and material data. Creating a relationship between the three which will be crucial in the modeling.

The non-Newtonain material used to be tested is the Oobleck fluid, which is a mixture of conrstarch and water. This type of non-Newtonian fluid exhibits a strong non-Newtonian behavior, which is evident as its viscosity changes to a large extent compared to other non-Newtonian fluids when force is applied. The viscosities of Oobleck fluid under diffferent concentrations are from the paper Estimation of viscosity and hydrolysis kinetics of corn starch gels based on microstructural features using a simplified model[4]. The concentration range in the paper is from 1:4 to 1:16 sample ratio of cornstarch to water.

The walking data and the GRF needed at different speeds are important to the viscosity of the material. A walking test is performed to get the corresponding time and initial velocity, while other information in walking data such as mass can be easily measured.

A slow-motion camera is used to film a persons feet in the test, which includes 4 walking speeds: walking, fast walking, jogging, and running. Each step consists of three parts: the first part is from when the front foot lands to when the back foot rises; the second part is from when the back foot leaves the ground and reaches the top; the third part is from when the back foot reaches the top to when the front foot touches the ground again. The first part is called the on ground time, and it donates the time variable in Eq.5. After filming, the number of frames in each part of the step was counted, and collected in time units of seconds. The camera used to film is 120 frames per second. This allows any change that takes longer thant 1/120 of a second to be captured. A step is divided into 3 parts, except for running which has 4. To make sure this data is correct, it is timed how long it takes to take 5 steps, and an estimate of how long it takes to take one step is calculated. The height of each step is collected as well as the time. These two pieces of information together give the initial velocity and time taken. The initial velocity is the heel height divided by the time of the feet moving from the top to touching the gound.

After substituting the data into Eq.5, a graph of GRF values in relation to viscosity is presented. It can be used in further comparison and analysis to determine the suitability.

The GRF data is collected from the table of GRF of different types of shoes measured by Kyung-Ok Yi in The Effects of Shoe Types on Ground Reaction Force[5]. Some graphs of the walking profile are also included later in the paper

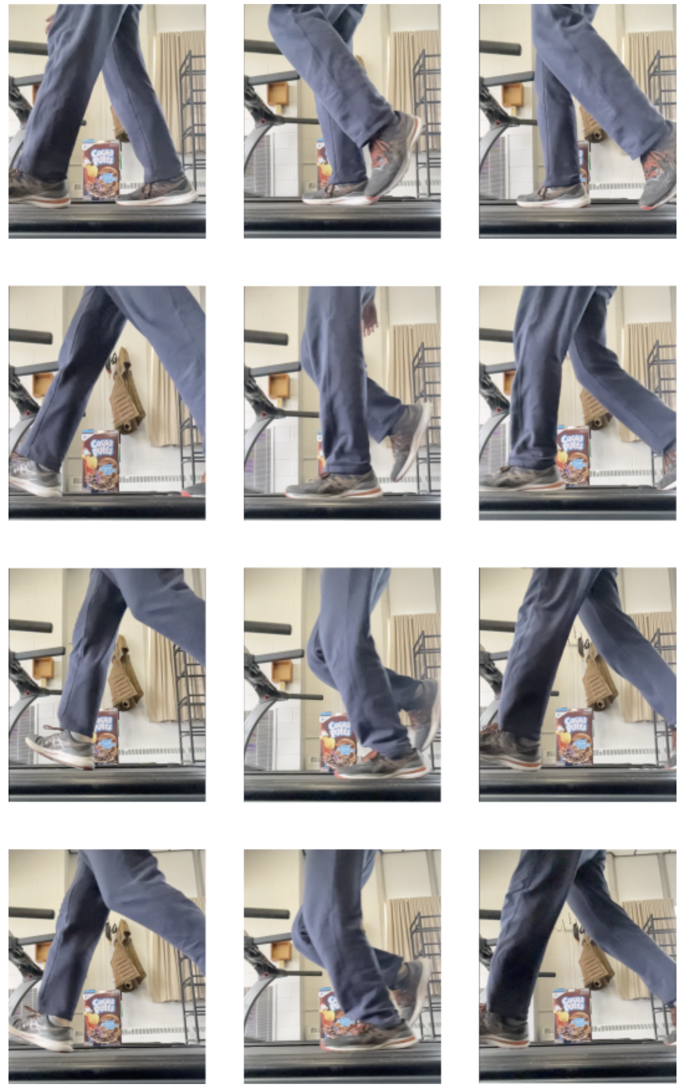

Fig. 1 The pictures are collected from the walking test, the first column shows the start of on-ground time, the second column shows the highest point the foot reaches, and the third column shows the time when the foot lands on the ground. The first row is walking, the second row is fast-walking, the third row is jogging, and the fourth row is running.

Results

For the specific case in this experiment, the weight of the test subject is 77kg, the age is 16 years old, and the gender is male. The shoe size is 42 in Euro standard. The area of the surface that interacts with ground is 240.3 cm^2. The gait of the steps are standardized where all legs and feet movements are parallel to the direction of the body movement.

In the table in Table.1, on-ground time is the time period from the front foot landing to the back foot leaving the ground. Ground-top is the period from when the foot leaves the ground until it reaches the highest point. Top-ground is the period from when the foot reaches the highest point to when it lands on the ground.

Running is different as the back foot leaves the ground before the front foot lands. The on-ground time for running is the time the back foot is on the ground during the start of the first step. Ground-top(1) is the part where the back foot lifts until the front foot lands, which is part of the ground-top(t) as it presents the total time of the back foot leaving the ground until it reaches the highest point.

Table.1 clearly shows how every walking speed differs between the time it takes in each part. When walking, the time for the whole step to complete is the longest compared to the others, but the time to lift the feet is faster than fast walking and jogging. The time on the ground is the time from the front foot landing to the time when lifting the back foot. The back foot is lifted before the front foot lands during running, so the on-ground time for running is calculated from the time when the foot touches the ground when we start running.

	walk #1	walk #2	walk #3	average			fast walk #1	fast walk #2	fast walk #3	average
total time (s)	0.75	0.84	0.75	0.78		total time (s)	0.5	0.53	0.48	0.5
on ground time (s)	0.24	0.25	0.22	0.237		on ground time(s)	0.175	0.15	0.175	0.167
ground-top time(s)	0.075	0.092	0.075	0.081		ground-top time(s)	0.1	0.11	0.083	0.098
top-ground time(s)	0.43	0.5	0.46	0.463		top-ground time(s)	0.31	0.275	0.225	0.27
	jog#1	jog#2	jog#3	average			run#1	run#2	run#3	average
total time(s)	0.42	0.46	0.42	0.43		total time(s)	0.375	0.38	0.36	0.372
on ground time(s)	0.017	0.025	0.01	0.017		on ground time(s)	0.12	0.11	0.11	0.113
ground-top time(s)	0.12	0.13	0.1	0.117		ground-top(1) time(s)	0.075	0.067	0.08	0.074
top-ground time(s)	0.28	0.3	0.31	0.297		ground-top(t) time(s)	0.16	0.15	0.16	0.157
						top-ground time(s)	0.29	0.3	0.28	0.29

Table.1 Table showing results from walking test in seconds. When running, the foot at the back leaves the ground before the foot in the front lands. Therefore, it is divided into the ground-top(1), which is before the front foot leaves the ground, and the ground-top(t), which is after the front foot lands on the ground and before the back foot reaches the top.

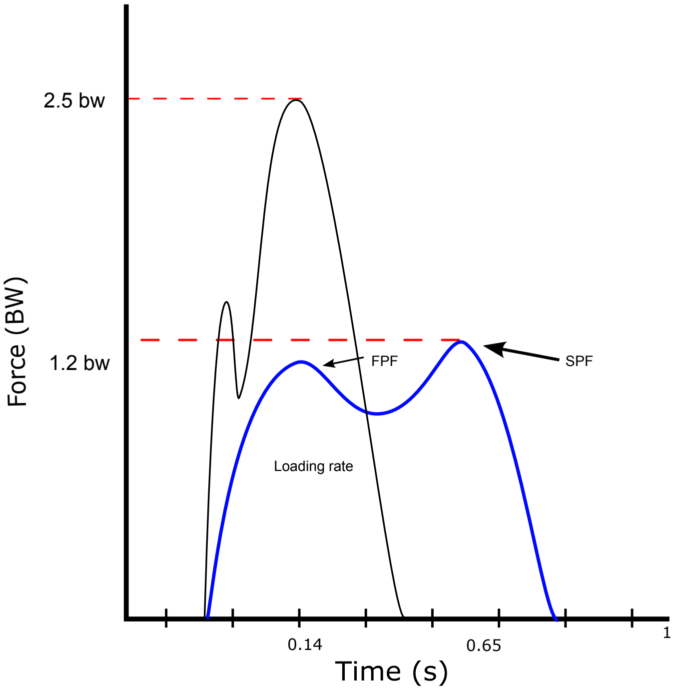

Fig. 2 This is a recreation graph from the paper Evaluating Sports Shoes Using Ground Reaction Force Data[6] by Joseph Hamill and the paper Comparison of Ground Reaction Forces between Combat Boots and Sports Shoes[7] by Rodrigo R.Bini et al. The black curve indicates the force corresponding to time during running, and the blue curve indicates the relationship when walking. The unit of force (BW) represents body weight. FPS means the first peak force and the SPF is the second peak force.

The graph in Figure 2 shows the time and the force of a step for both walking and running. The shape of the curves shows that there are two times that the step gives pressure to the ground. The latter one has the most pressure, which means that the force and GRF values we measured correspond to this peak. The contrast between the curves shows that a step during walking does take a longer time, and applies a lower force than running.

Table 2: Table showing Ground Reaction Force (GRF) for different fluid viscosities under tested walking speeds.

Viscosity	Walking GRF	Fast Walking GRF	Jogging GRF	Running GRF
1500	0.22	0.28	0.54	1.12
768	0.15	0.2	0.36	0.73
422	0.1	0.13	0.23	0.45
112	0.03	0.04	0.07	0.13
111	0.03	0.04	0.07	0.13
74	0.02	0.03	0.05	0.09
62	0.02	0.02	0.04	0.08
4	0	0	0	0

Table.2 is the GRF each level of viscosity of fluid will give at different walking speeds. This presents how much force is being applied to the user and gives a clear set of data about the different GRFs when working with different viscosity. While Running and Jogging have a very similar GRF, they differ to a sizable degree from the walking and fast walking GRF.

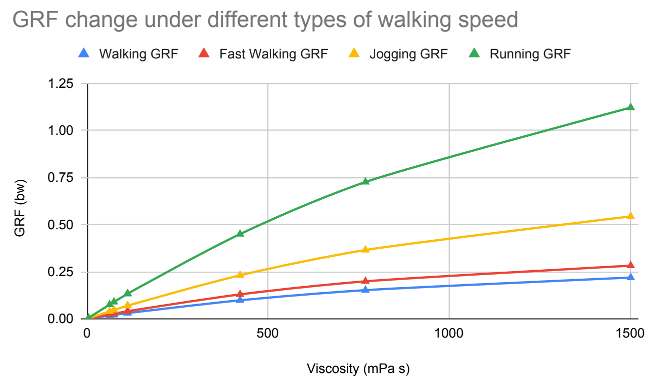

Fig. 3 Graph showing Ground Reaction Force (GRF) for different fluid viscosities under tested different walking speeds.

Figure 3 shows the trend of how the GRF changes when different viscosity is applied under different speeds of walking. Undoubtedly, with the increase of the viscosity, the GRF will increase respectively. Although the speed of walking and fast walking do not differ as much as the other speeds, the difference in the GRF they give is much closer. We can conclude that when we are walking slowly, the GRF acting on us doesnt do much work, and doesnt differ too much.

Discussion

Analysis of Results

Substituting GRF values from different activities into the graph can help to obtain a suitable viscosity. Other studies which measured GRFs for currently available shoes were investigated, and some results shown in Table.3.

Every square point on the line represents the viscosity of a specific ratio of cornstarch and water, which allows us to quickly identify how to make the mixture after matching the GRF.

The GRF of different walking states can be evaluated and compared to the GRF value of existing shoe types. In addition, the difference between the GRF values can be examined to check if the shoe sole will meet the required hardness when pressure is applied during movements.

We should compare the leisure shoes with the walking GRF since the main use of these shoes are for more comfortable un-sports related activities. Comparing the data in Fig.4 and Table.3, the GRF of flip flops and canvas shoes which are leisure

Table.3 This is the table of GRF of different types of shoes measured by Kyung-Ok Yi in The Effects of Shoe Types on Ground Reaction Force[5].

Types of shoes	GRF(bw)	N	SD
Barefoot	0.76	10	0.23
Five-toed shoes	0.78	10	0.24
Elevated forefoot walking shoes	0.77	9	0.33
Elevated mid-foot walking shoes	0.53	9	0.28
Flip flops	0.45	9	0.07
Canvas shoe	0.41	6	0.26
Running shoes	0.24	10	0.28
total	0.57	63	0.32

Table.4 This table is from the paper Estimation of viscosity and hydrolysis kinetics of corn starch gels based on microstructural features using a simplified model[4]. It indicates the viscosity of Oobleck with different concentrations of water to starch.

Sample ratio of cornstarch to water	Viscosity (mPa s)
1:04	768 23
1:06	422 27
1:08	112 30
1:10	111 15
1:12	74
1:14	62
1:16	48

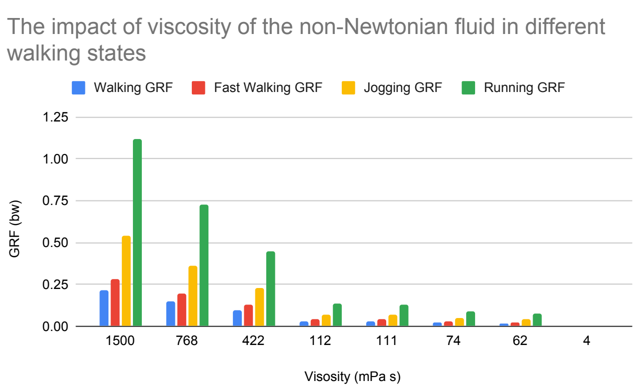

Fig. 4 A graph generated using table 2 to visualize the difference in GRFs under different walking states at different original viscosity.

shoes do not have a matching GRF under walking state in any viscosity, represented by the blue bars. The only matching GRF is the GRF of running shoes with the GRF of 1500Pa s ordinary viscosity. Unless the user has a special requirement of softer shoe soles, such as wearing running shoes as leisure shoes, normal cornstarch and water solution does not meet the requirement to support the comfortability of a pair of shoes.

When examining the maximum GRF of each fluid shoe sole, we should compare the GRF under running state of each viscosity with barefoot and five-toed shoes. Due to the feet-to-ground firction and explosivness the user needs when making quick turns and sudden acclerations during sports activities, the maximum GRF needed from the shoe soles should be the GRF of barefood and five-toed shoes. In the data in Table 2, the fluid sole with original viscosity 768 has a GRF of 0.73 bw under running state. This a close value compared to the GRF values of barefoot and five-toed shoes. Therefore, a fluid shoe sole with 768Pa s original viscosity will have a suitable support in sports acitivities. In Table 4, this corresponds to a cornstarch to water ratio of 1:4.

The difference between walking state and running state and the difference between the leisure shoes GRF and maximum sports need GRF is also essential to the analysis. If there is any method to increase the overall GRF value of the shoe soles. The concentration of cornstarch to water with the viscosity corresponding to a suitable GRF difference between the walking state and running state will be an ideal choice. According to Table 3, the mean of leisure shoes GRF (flip flops and canvas shoes) is 0.43bw, and the mean of maximum sports need GRF (barefoot and five-toed shoes) is 0.77bw. The difference between them is 0.34bw. Visualized in fig.4 and calculated using Table 2, the fluid sole with an original viscosity of 422Pa s has the most suitable difference between walking and running state, 0.35 bw. In Table 4, this corresponds to a cornstarch to water ratio of 1:6.

In Fig.4, the difference of GRF between the four walking states increases exponentially as the velocity of the walking state increases, same in all original viscosities. This implies that the GRF will remain relatively stable when the pressure applied on it is low. When high pressure is applied, extreme situations are implied such as sudden turns and accelerations, which requires much more support than usual. The exponential curve will release a strong GRF, which would provide enough support.

Other Considerations

The GRF values that this paper provides give a clear idea of how non-Newtonian fluids can be used as a material for shoe soles, and which ratios are suitable. Although this paper emphasizes the relationship between the concentration of cornstarch and water in shoe soles for various kinds of walking speeds, the relationship between the GRFs and viscosity is the most valuable output, due to the difference in peoples weight and difficulty in using cornstarch in manufacturing shoe soles.

Other solid materials also output a different GRF under different walking speeds. However, since they have a constant hardness, it is presented as a straight line in Figure 5. On the

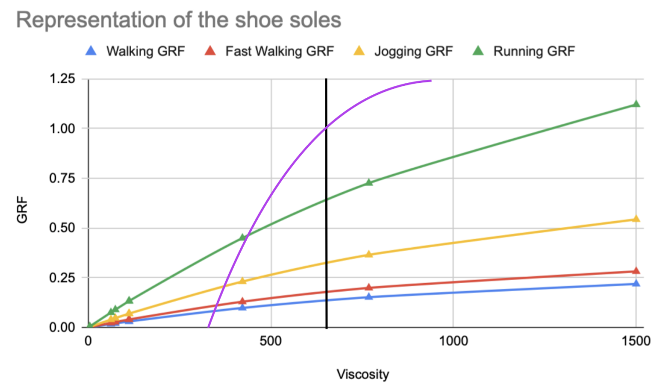

Fig. 5 The graph is a sketch map that shows how non-Newtonian fluid shoe soles are different from the normal ones. The purple line represents the non-Newtonian fluid shoe soles, and the black line represents the normal shoe soles. These lines are not drawn from accurately measured values, only an example showing how the curve will look like.

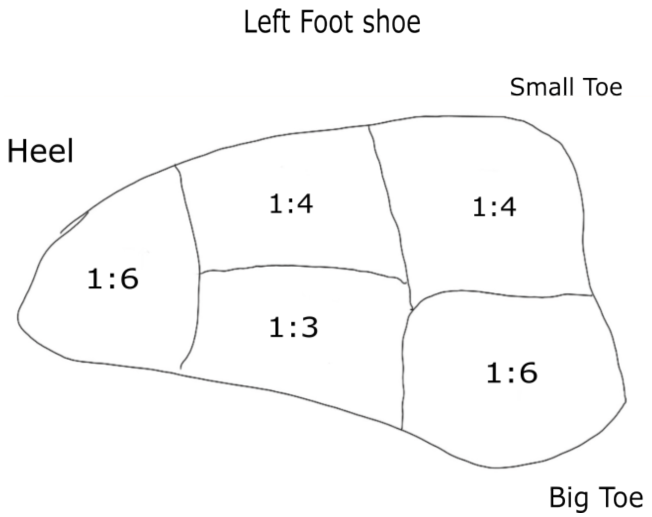

Fig. 6 An example of the separation of non-Newtonian fluid of sacs in the midsole of a shoe, with the number shown is the ratio of cornstarch to water. This is just a sketch instead of a precisely calculated model.

other hand, non-Newtonian fluid extends this difference and allows more support under pressure and more comfortability under less pressure, which is a curved line in Figure 8 as shown below.

The changing viscosity example outlines this characteristic as it shows a GRF almost reaching elevated forefoot walking shoes or even barefoot when running, but exhibiting a soft bottom when walking, which is softer than most of the shoes we have. This phenomenon allows the shoes to give strong support when users are exercising, where a huge pressure is being applied. When the users are relaxing, or walking, the much lower pressure will direct the shoe soles to be softer, and it will be very comfortable as only a small support is needed.

By comparing to the 2D and 3D pressure map in the Pedar-x program presented in the paper Does in-shoe pressure analysis to assess and modify medical grade footwear improve patient adherence and understanding[8], a sketch of how the non-Newtonian fluid sacs might by arranged is presented in Fig.6.

Although the performance of non-Newtonian Fluids is more flexible than the other materials, there are two more areas to consider: manufacture and durability.

Cornstarch and water are both very cheap materials and are very common all over the world. Due to their availability, such a sole could be the cheapest part of the whole shoe manufacturing process. It is also very environmentally friendly, as both of them are organic materials which are biodegradable.

However, its durability doesnt really fit the requirements. As a pair of shoes, it needs to be stable and at least last 3-5 years. Water and cornstarch are both organic materials, which contain bacteria and may degrade over time. One method to counter this is to heat both of them up and quickly put them into a vacuum space so no bacteria will be in the material.

Another option is to use a non-organic non-Newtonian fluid. Many industries provide non-organic non-Newtonian fluids made of metals and deionized water. They are much more useful in manufacturing shoes but they might be more expensive and cause more environmental damage than cornstarch and water. Except for this issue, cornstarch itself is a suitable material. While encountering all the non-Newtonian fluids, it can easily achieve better performance and required durability and manufacturing restrictions.

Conclusions

An example ratio of water to cornstarch to create a pair of comfortable and supportive shoe soles is found, and an equation relating GRF and viscosity is analyzed. The values of forces applied to the soles are found through Eq.4 and the walking test, allowing GRF values to be compared with other shoes. This helps to choose the correct viscosity and the corresponding ratios, for a non-Newtonian Fluid shoe sole.

As discussed in the result, an overall ratio of 1:4 or 1:6 of cornstarch to water is the most suitable ratio we found. The former one gives the provides a suitable maximum GRF while the user feels comfortable when the shoe sole is soft in leisure conditions. The latter one provides a suitable increase of GRF with the increase of pressure applied. If any factor can increase the GRF of the solution as a whole, such as temperature, this solution would be the best to suit the changing needs of leisure shoes and sports shoes. To be more accurate and meticulous, as discussed in the results, different mixtures can be used in different sacs corresponding to each part of the foot so that each part can reach its best performance.

This research includes the changes in non-Newtonian fluid, the relationship between viscosity and GRF, and the actual availability and use of cornstarch and water in shoe production. It is shown that non-Newtonian fluid can be a useful material for shoe soles with scope for mass production.

A drawback of this method is that the viscosity and viscosity change as the pressure changes cant be directly calculated, and there are not many values available for non-Newtonian fluids except for Oobleck. This makes it very hard to compare other non-Newtonian fluids to select the best choice.

As Oobleck is an organic non-Newtonian fluid made of cornstarch and water, other nonorganic ones might be a better choice if experimental data is available. To improve on the current method, an equation that calculates the change in viscosity of a non-Newtonian fluid by its particles size, intermolecular forces, and the fluids polarity will help the most. This can allow a relationship between the basic characteristics of a non-Newtonian fluid and the concentration it needs for a certain viscosity, giving a much more general relationship than is studied in this paper. This would help to adapt other non-Newtonian fluid choices as shoe soles. Any other polymer resin or viscous fluids are suitable. Although strong non-Newtonian behabior is favored in this situation to change the stiffness of the shoe soles in response to the user.

Another issue is the fact that precise techniques were not used due to their high cost. Experimental data found online is restricted to specific criteria which makes general comparison hard. Also, despite using slow motion and counting frames to make the timing in the walking test as accurate as possible, there will be errors in the data collected. This might cause a mistake in the measurement, but not as large enough to change the overall results.

This research indicates that if different properties of liquids are applied to shoes, more functions can be discovered. To exhibit a smart behavior, fluids are the best choices to be considered and studied. As more tools are developed to create better integration in manufacturing, non-Newtonian fluids can exhibit their characteristics on a wider scale.

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