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Article

Design Optimization of Ballet Shoes for Beginners Using Computer Simulation with Musculoskeletal Model

Changmin Pyo

IM Virtual Design Task, LG Display, Pa-ju, 10845, Korea; changmin.pyo@gmail.com; Tel. +82-10-8512-2537

Abstract: The beautiful and stable posture is essential for ballet. Especially the pirouette which dancers balance themselves on their one leg is one of the most impressive postures. During the pirouette motion, loads from the rotation and the body weight are concentrated to the one leg. Proper ballet shoes can reduce the muscle burden and improve the stability. Four types of shoes; bare feet, running shoes, pointe shoes, and dance sneakers are analyzed. The motion capture system and SIMM are used for the analysis of muscle burden and stability during pirouette. The major 6 muscles in the leg (beceps femoris long head, beceps femoris short head, soleus, rectus femoris, gastrocnemius medialis, and gastrocnemius lateralis) are analyzed, and the effect of rotating velocity is considered. Dance sneakers are outstanding for improving the stability and lessening the muscle burdens in all conditions for beginners. That comes from the design feature of the divided shoe soles and protecting the ankle of the axis leg. With the results and analysis, the direction for design optimization of ballet shoes is suggested. Consequently, this research is about the verification of sports equipment using computer simulation with the musculoskeletal model from a scientific viewpoint of biomechanics.

Keywords: Design optimization; Computer simulation; Musculoskeletal model; Biomechanics; Ballet shoes; Pirouette

1. Introduction

Nowadays, people are interested in various exercises for healthcare and pleasure including difficult sports for beginners such as ballet. However, the motion of ballet is hard, dangerous and high loaded to muscle. Especially the pirouette rotating with one leg needs many practice and strong muscle. The process is shown in Figure 1. As the loads from whole body weight and the rotation concentrate one leg, people should take care. Ballet shoes can be good devices for reducing the muscle burden and developing stability simultaneously. Thus the design optimization of ballet shoes is very meaningful for people including beginners.

From the viewpoint of consumers, such healthcare equipment should be investigated for its safety and functionality. With this objective, several verification trials have been conducted; however, most certification processes relied on direct experiments alone. For instance, the health care shoes were examined with a direct experiment that measured the change in muscle electric current using electromyography (EMG) or video analysis [1-5, 9, 12]. However, image analysis performed using a video camera is qualitative and not quantitative in nature. EMG also has other demerits, as its results can vary from person to person, depending on their skin condition and the depth of their fat layer [13]. As EMG can prohibit the intended motion, EMG is not proper to active motions of the beginners such as dance. Pirouette is one of fast motions in Ballet. Actually we tried to attach EMG to the subjects, but it did not work. The equipment prohibited the motions, and beginners were concerned about EMG equipment during their movement. Therefore, we suggest computer simulations with motion capture in order to examine the effectiveness of ballet shoes. Firstly, simulation is performed with a computer-developed model with the motion capture data and inverse dynamic calculation is carried out in order to obtain the activation of muscles. For this

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purpose, we used SIMM (Software for Interactive Musculoskeletal Modeling), a computer program that can develop and analyze a model of the human body. The accuracy of SIMM has been acknowledged in several papers and journals [10, 11, 14-22]. Especially SIMM is the very powerful tool for analyzing the motion of the lower limb such as the gait. [10, 11, 14]

(**a**) (**b**) (**c**)

Figure 1. Process of Pirouette (**a**) Preparation; (**b**) Plie; (**c**) Releve.

Analysis of the lower limbs using computer simulation with the musculoskeletal model was performed before. Park & Pyo analyzed the effectiveness of ballet shoes with computer simulation, but that analysis had limitation. Only 4 muscles were analyzed, rotating velocity was not considered as conditions, and there was not enough research of stability during rotation [17].

This research covers analysis of 6 major muscles of a leg, 2 conditions of velocities, and 4 types of shoes; bare feet, running shoes, pointe shoes, and dance sneakers. The muscle burden and stability during pirouette are compared among the shoes and conditions, and the direction of design optimization is suggested.

Muscle forces calculated by computer simulation are muscle burdens, and muscle burdens are negative for sustainable movements. Thus many researchers have focused on the assessment and reduction of muscle burdens with the physiological point of view [7, 8].

Every analysis is based on the computer simulation with musculoskeletal model from a scientific prospect of biomechanics.

2. Materials and Methods

2.1. Subject & Study Protocol

Six healthy males volunteered to participate as subjects in this study; one is in novice high level and the others are beginners. The relevant characteristics of the subjects are listed in Table 1.

Table 1. Subject characteristics (N = 3).

	Average	Standard Deviation	Range
Age (years)	23.8	1.7	21–26
Weight (kg)	70.5	13.5	60–84
Height (cm)	176.3	7.9	165-186
Foot size (mm)	275.8	9.2	260-285
Experience in ballet dance (years)	0.8	0.8	0.2-2.4
Rotating Velocity (Fast mode, rad/s)	2.5π	0.1π	2.3π-2.6π
Rotating Velocity (slow mode, rad/s)	2.0π	0.1π	1.8π-2.1π

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The analysis of dancing shoes is one of the main purposes of this research. Thus three types of shoes; running shoes, pointe shoes, and dance sneakers are chosen and compared with bare feet.

The main feature of pointe shoes is dividing the front and back soles for moving feet freely. The thickness of soles is from 1mm to 4mm, other parts of shoes are very thin, so the shoes look like the thin leather wrappings for feet. The side and bottom views of a pointe shoe are shown in Figure 2. While dance sneakers for ballet look like normal shoes, their front and back soles are divided such as the pointe shoes. The thickness of soles is 10mm. The side and bottom view of a sneaker are shown in Figure3. The difference from pointe shoes is that dance sneakers protect the ankle of feet. Finally, normal running shoes are chosen. The shape is similar to that of dance sneakers, but it is composed of only one shoe sole as Figure 4. The thickness of the sole is above 20mm.

(**a**) (**b**)

Figure 2. Pointe shoes (**a**) Side view; (**b**) Bottom view.

(**a**) (**b**)

Figure 3. Dance sneakers (**a**) Side view; (**b**) Bottom view.

(**a**) (**b**)

Figure 4. Dance sneakers (**a**) Side view; (**b**) Bottom view.

2.2. Measurement Equipment & Data Collection

Qualysis Motion Capture System (Qualysis, Gothenburg, Sweden) was used in this study. Ten Qualysis cameras operating at a uniform rate of 60 Hz recognized movements corresponding to the displacement of markers attached to the subjects' bodies [23].

The ground reaction force (GRF) during ballet was measured using two AMTI force platforms (Model OR6-7, Advanced Mechanical Technology Inc., Watertown, MA, USA). The GRF data were

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filtered through a low-pass filter at 25 Hz. They are shown in Figure 5, and the layout of equipment is shown in Figure 6.

(a)

(b)

Figure 5. Measurement Equipment (**a**) Qualysis Motion Capture Camera; (**b**) AMTI force platforms.

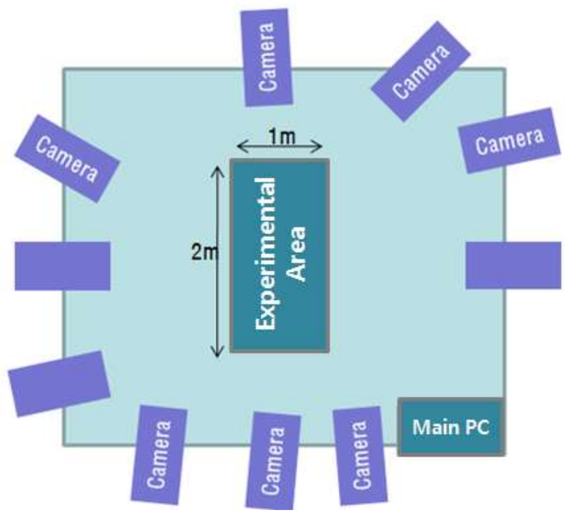
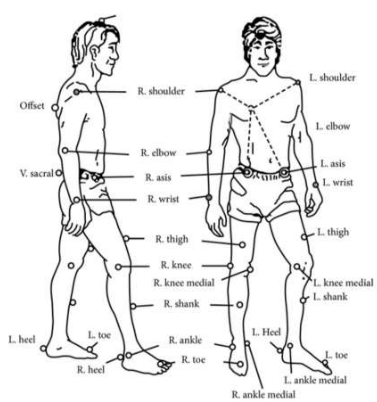


Figure 6. A Layout of Motion Capture Cameras and Force Plate.

In order to capture motion and analyze muscle activation, markers were placed based on the Helen marker sets [15], as shown in Figure 7. The reaction force data for each foot were measured using two force plates during pirouette. Each plate instantaneously measured the magnitude and direction of forces when subjects stepped on it.



(**a**)

(**b**)

Figure 7. Placement of Helen-Hayes marker set (**a**) Manual; (**b**) Application to Specimen.

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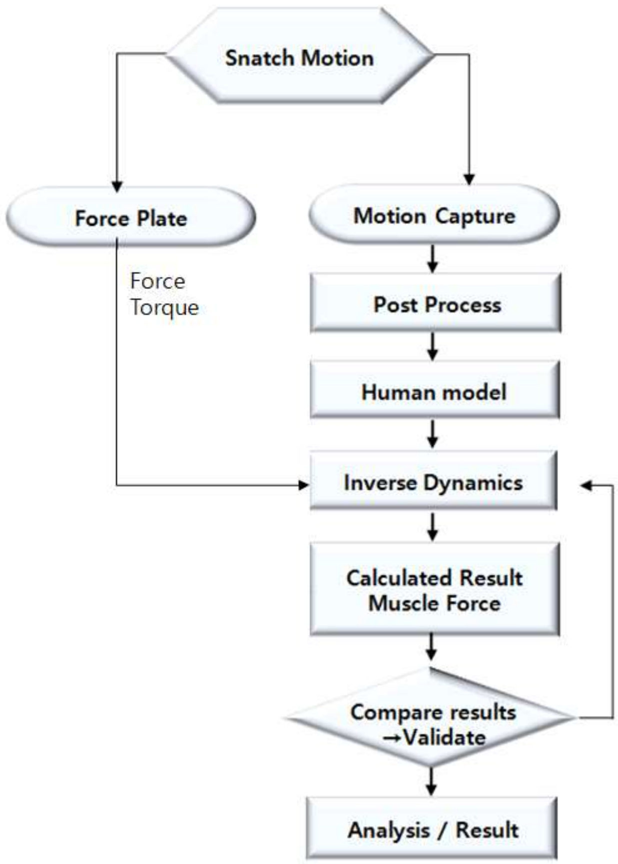
2.3. Computer simulation

We used a musculoskeletal model of each individual by scaling a generic full-body model (MusculoGraphics, Inc., Chicago, IL, USA) in order to perform the analysis using SIMM. The current posture of an articulated body was detected by matching the projections of a kinetic model with the detected set of marker points, based on the marker data tracked in a static pose. This model had 328 body segments, 37 joints, 55 degrees of freedom, and 94 muscles [24]. The mechanism of muscle is Hill type muscle which is applied for many types of musculoskeletal models [25].

SIMM analyzes the muscular burdens and changes in muscle activity of the model using motion and force platform. The torque applied to joints is calculated by the method shown in Figure 8. Final muscle forces are calculated based on trial and error method, and static optimization method is used for the accuracy and the fast speed of calculation. The position, velocity, acceleration, and the forces from the force platform are used to determine the joint torques and muscle forces [15, 26].



(**a**)

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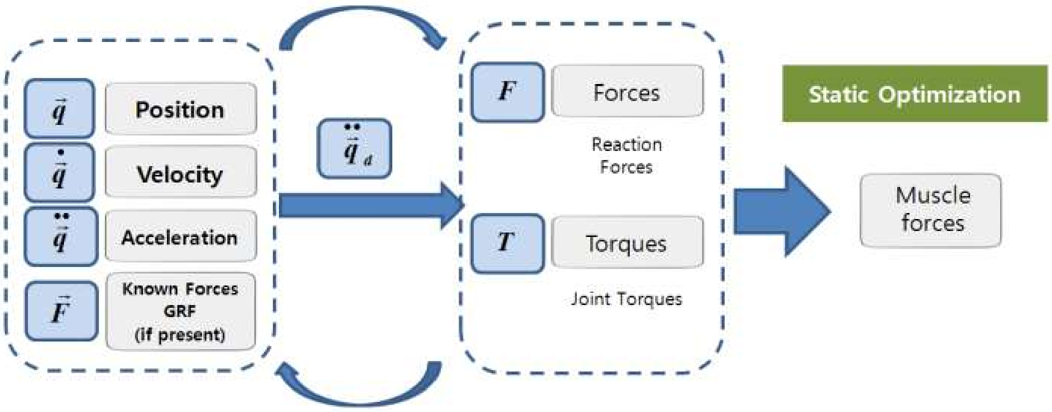

(**b**)

Figure 8. Computer simulation algorithm flowchart (**a**) Overall Process; (**b**) Inverse Dynamics.

Inverse dynamics is important for computer simulation [26]. The joint torque is calculated from the motion data input as follows. First, the ideal acceleration is calculated from the kinematic data from experiments and the current condition data of the musculoskeletal model with Expression (1). When the desired acceleration is determined from Expression (1), the velocity error and position error are induced to zero, which is expressed by the second order differential equation in Expression (2). By removing the errors, we can finally determine the results based on the joint torques or inverse dynamics.

$$\ddot{\vec{q}}_d = \ddot{\vec{q}}_{\exp} + k_v(\dot{\vec{q}}_{\exp} - \dot{\vec{q}}) + k_p(\vec{q}_{\exp} - \vec{q}) \tag{1}$$

$\ddot{\vec{q}}_d$: Desired acceleration

$\ddot{\vec{q}}_{\exp}$: Experimental acceleration data

$\dot{\vec{q}}_{\exp}$: Experimental velocity data

$\vec{q}_{\exp}$: Experimental position data

$\dot{\vec{q}}, \vec{q}$: Generalized data (velocity, position)

$$\ddot{\vec{e}} + k_v\dot{\vec{e}} + k_p\vec{e} = 0 \tag{2}$$

$\ddot{\vec{e}}$: Acceleration error $(\ddot{\vec{q}}_{\exp} - \ddot{\vec{q}}_d)$

$\dot{\vec{e}}$: Velocity error $(\dot{\vec{q}}_{\exp} - \dot{\vec{q}}_d)$

$\vec{e}$: Position error $(\vec{e}_{\exp} - \vec{e}_d)$

k_v, k_p : Feedback gains

3. Results

Six main muscles of the lower limbs were analyzed, and they are shown in Figure 9 [27].

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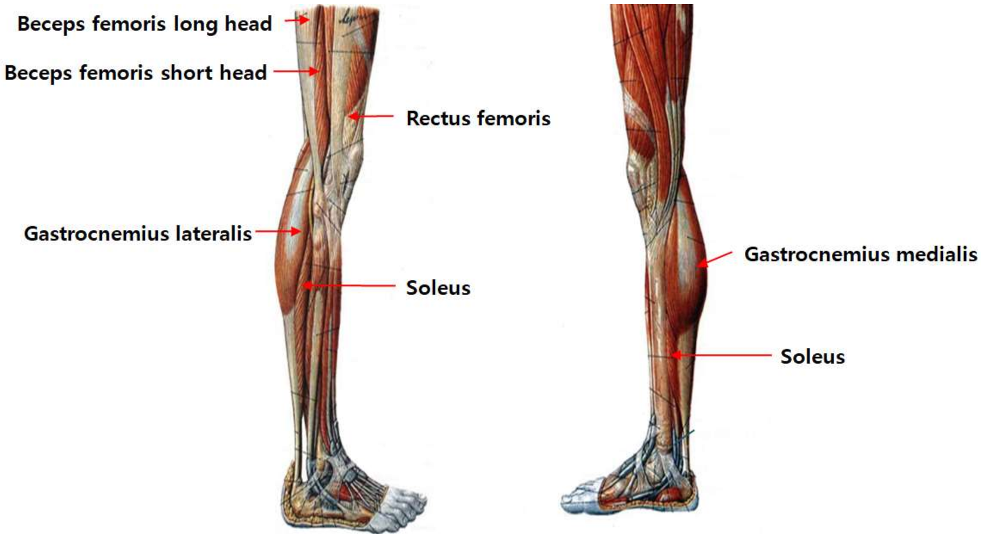
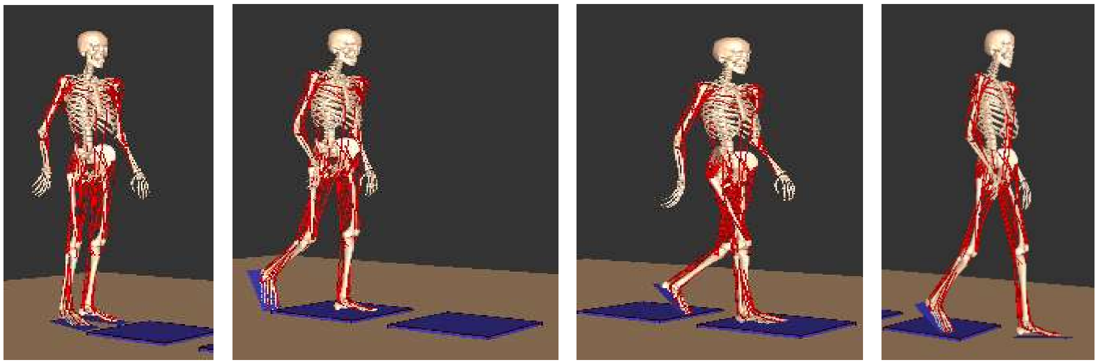


Figure 9. Analyzed muscle in the lower limb.

3.1. Reference Muscle Burden (Gait)

As the muscle force during pirouette was different among people, the normalizing process among the subjects was essential. Thus the maximum force of each muscle during the gait with running shoes was selected as the standard force of each specimen. The quantities of muscle burden have difference according to the subjects. Thus the proportion of muscle burden compared to the normal gait is considered. That's for exclusion of the individual variation.

The gait cycle is shown in Figure 10, which described the left leg put on the plate first. The representative calculated muscle burden of the left leg during the gait is shown in Figure 11.



(**a**) (**b**) (**c**) (**d**)

Figure 10. Gait cycle (**a**) 0%; (**b**) 40%; (**c**) 77%; (**d**)100%.

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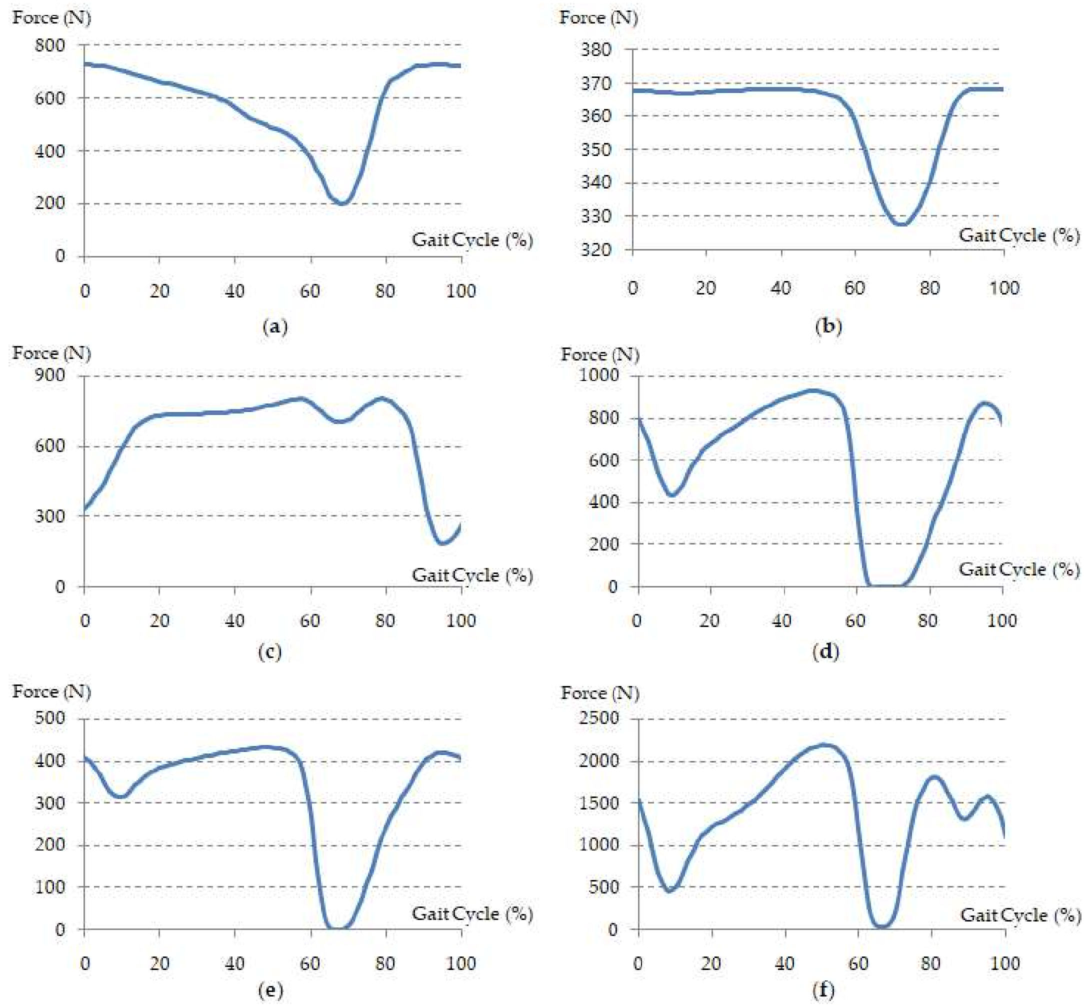

Figure 11. Left leg muscle burden during gait represented by one dancer (**a**) Biceps femoris long head ;(**b**) Biceps femoris short head; (**c**) Rectus femoris; (**d**) Gastrocnemius medialis; (**e**) Gastrocnemius lateralis; (**f**) Soleus.

The average and maximum force of each muscle are shown as Table 2. The maximum force of each muscle was used as the reference.

Table2. Example of Muscle burden during gait of one dancer (Unit: N).

	Average	Maximum
Biceps femoris long head	572.8	727.4
Biceps femoris short head	360.1	368.2
Rectus femoris	653.6	802.2
Gastrocnemius medialis	595.3	927.9
Gastrocnemius lateralis	326.9	432.5
Soleus	1335.0	2191.8

3.2. Muscle Burden During Pirouette

One cycle of pirouette is defined from preparation to landing with two legs, and it is shown in Figure 12. All the subjects are novices, so the first one cycle is analyzed. Experiments are done after enough practices and breaks. As the effect of the rotating velocity was also considered in this research, experiments were performed with two types of velocity conditions; the slow mode, and the fast mode. Detail velocities are shown in Table 1. The result of slow and fast rotation is shown in

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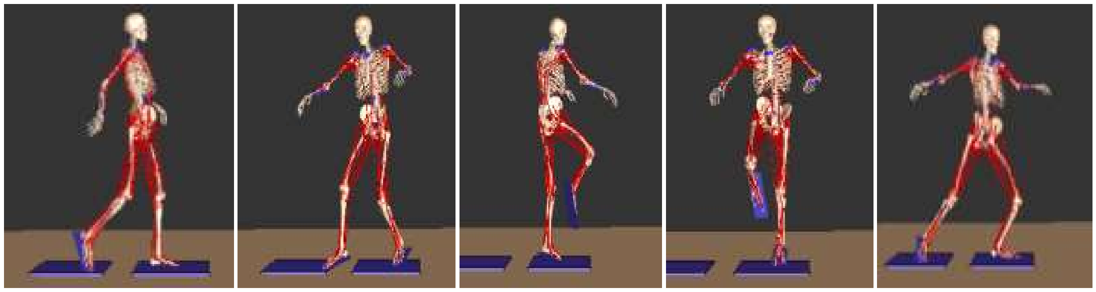
Figure 13, and Figure 14. Forces were normalized with the maximum muscle burden during the gait.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 12. Pirouette postures during one cycle (**a**) 0%; (**b**) 28.8%; (**c**) 43.8%; (**d**) 65.0%; (**e**) 100%.

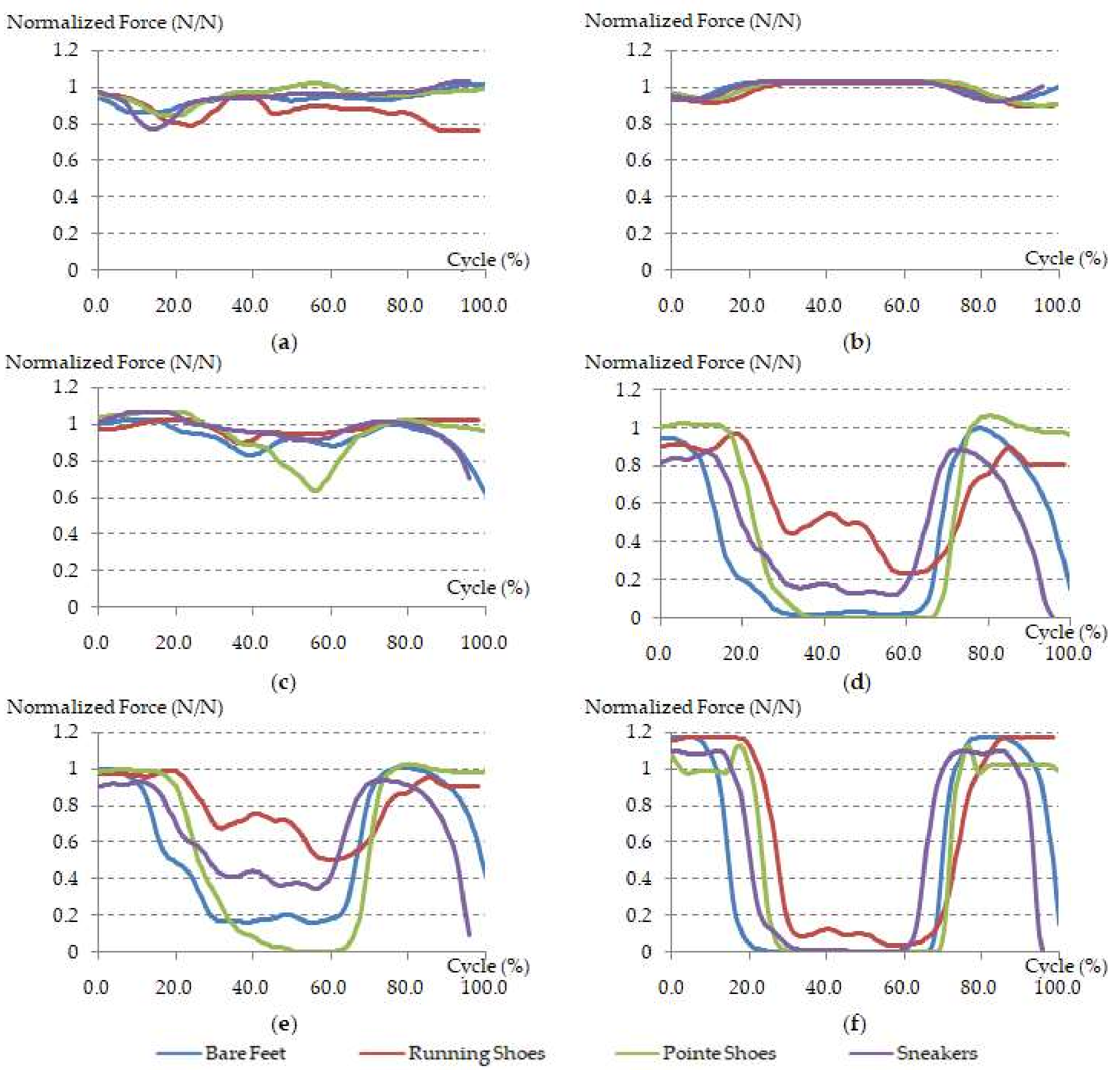


Figure 13. Muscle Burden with slow spin represented by one dancer (**a**) Biceps femoris long head (**b**) Biceps femoris short head; (**c**) Rectus femoris; (**d**) Gastrocnemius medialis; (**e**) Gastrocnemius lateralis; (**f**) Soleus.

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Table 3. Maximum Muscle Burden with the slow motion represented by one dancer (Unit: %).

		Bare Feet	Running Shoes	Pointe Shoes	Dance sneakers
Thigh	Biceps femoris long head	102.68	102.73	103.48	103.47
	Biceps femoris short head	102.75	102.71	103.48	103.38
	Rectus femoris	102.05	102.10	106.63	106.64
Calf	Gastrocnemius medialis	100.19	97.00	106.46	88.58
	Gastrocnemius lateralis	101.07	99.34	102.69	93.78
	Soleus	117.51	117.47	112.69	109.92

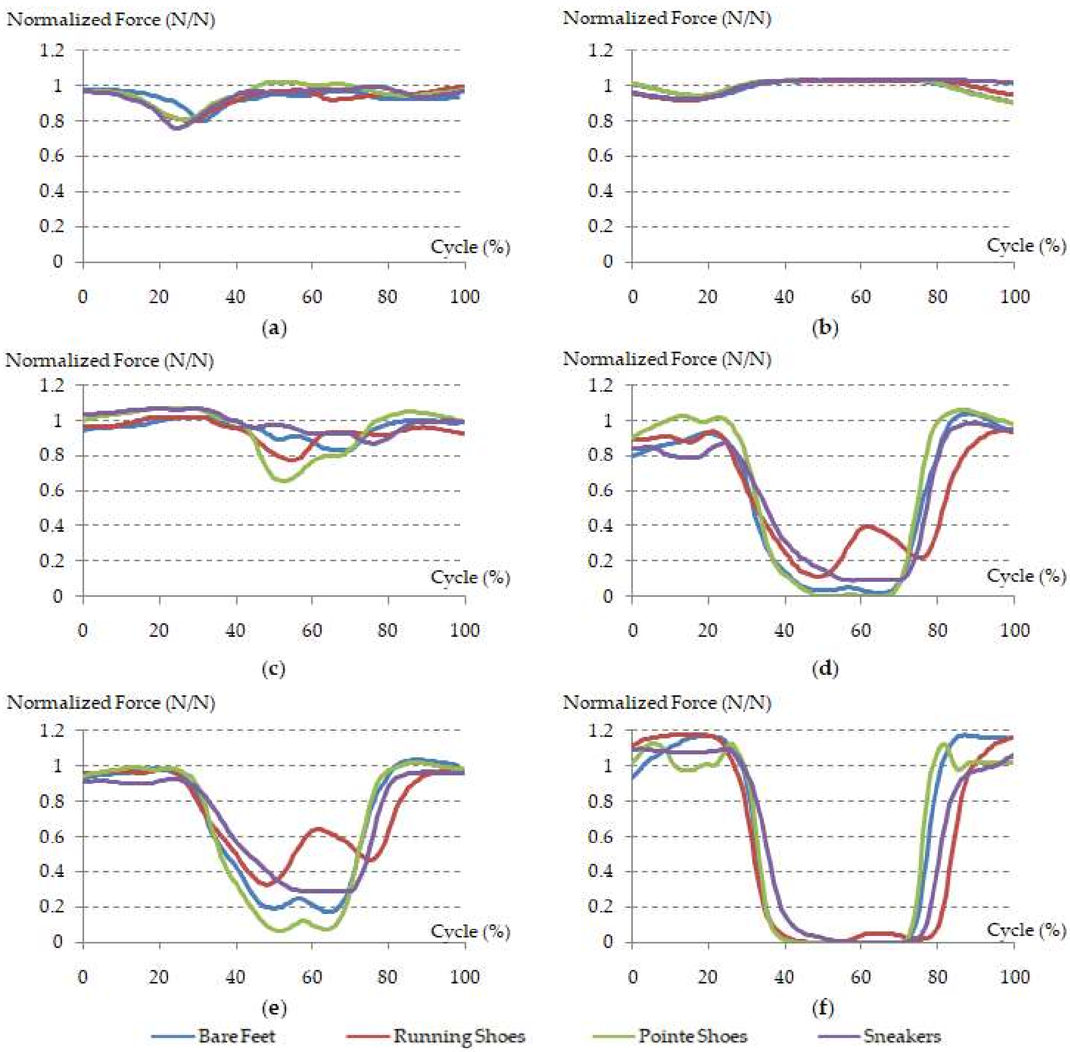

Figure 14. Muscle Burden with fast spin represented by one dancer (**a**) Biceps femoris long head (**b**) Biceps femoris short head; (**c**) Rectus femoris; (**d**) Gastrocnemius medialis; (**e**) Gastrocnemius lateralis; (**f**) Soleus.

Table 4. Maximum Muscle Burden with the fast motion represented by one dancer (Unit: %).

		Bare Feet	Running Shoes	Pointe Shoes	Dance sneakers
Thigh	Biceps femoris long head	97.87	98.97	102.10	99.47
	Biceps femoris short head	102.68	102.73	103.48	103.47
	Rectus femoris	102.10	102.10	106.64	106.64
Calf	Gastrocnemius medialis	103.87	94.13	106.04	98.54
	Gastrocnemius lateralis	103.30	98.67	102.31	96.58
	Soleus	117.50	117.49	112.69	109.92

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The maximum normalized forces during pirouette are shown as Table 3, and Table 4. The pirouette posture affected more muscle burden to the calf than the thigh for the beginners. The load to soleus was evident, above 10 % of additive burden was affected in comparison to normal gait. As the view of performance, dance sneakers were the best case among all shoes including bare feet. Around 5-10% amount, burden reduction was applied to the muscles of the calf. The effect of spin velocity was not obvious, but the performance of dance sneakers was restrictive in the fast condition. As the fast rotation was difficult to the beginners, the effect of ballet shoes could be restricted. However the effect of soleus was still available.

3.3. Eccentricity & Stability During Pirrouette

During pirouette, stability is essential for the safety of the dancer as well as maintaining accurate posture. To measure stability, we measured the distance between sacral and the left toe. That is shown in Figure 15. We then investigated stability by measuring the average and standard deviation of the sacral-toe distance for all the shoes. The left toe represented the axis during pirouette, and the sacral meant the center of mass. We made the assumption that the center of mass was the sacral, because the sacral was the nearest position to the real center of mass for the attachment of a marker. The distance during one cycle of pirouette is shown in Figure 16.

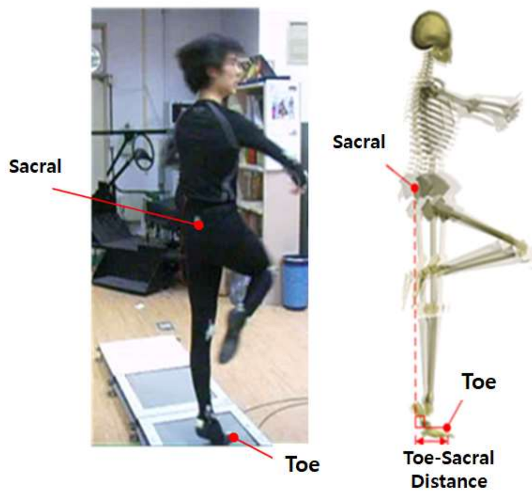

Figure 15. Definition of Stability (Sacral-Toe Distance).

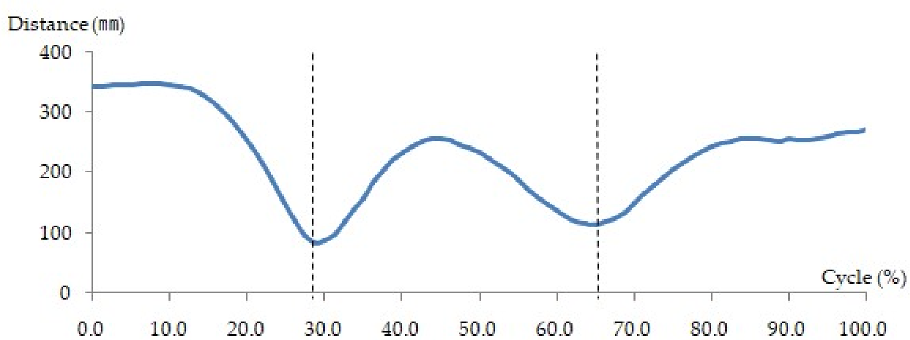

Figure 16. Sacral-To Distance represented by one dancer (Bare Feet Case).

In the cycle, ideologically, the subject should maintain the posture. However, if a balance is disturbed, the body will shake to correct the posture, and the distance between the sacral and the toe will increase. We focused on the period of real rotation which is from 28.8% to 65% of a cycle. The average represents the eccentricity between the rotation axis and the center of mass. The

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stability can be represented the change of the axis during the rotation. Though the change of axis can be explained with many statistical values, we choose the range meaning the difference of max and min. Because it is based on the run-out of axis and also it is easy and intuitive. The result is shown in Table 5.

Table 5. Sacral-Toe Distance represented by one dancer (Unit: mm).

Shoes Type	Slow motion		Fast motion	
	Average	Range	Average	Range
Bare Feet	160.8	146.2	176.1	173.3
Running Shoes	210.8	141.8	204.5	129.4
Pointe Shoes	196.2	97.8	222.4	117.9
Dance sneakers	195.8	80.7	217.2	107.8

All the shoes did not contribute to the improvement of the eccentricity of the center of mass, and there were worse results in the fast condition. All the shoes prohibited the free movement of the muscle of the foot sole. That affected to beginners strongly. However ballet shoes helped the improvement of stability during rotation, the effect of dance sneakers is superb in any conditions. The shape of covering the ankle caused that effect.

4. Discussion

The effect of two types of ballet shoes, running shoes and bare feet was verified using the computer simulation with the musculoskeletal model. As design differences among the shoes affected the gap of performance, we analyzed the structure of shoes and suggested the design optimization of ballet shoes for beginners.

4.1. Analysis

The average and the standard deviation of maximum muscle burden in slow and fast motion are shown in Table 6 and Table 7. Ballet shoes affect the release of calf, and the effect of sneakers is distinct. The rotating velocity does not make the obvious difference in the view of muscular relaxation. Generally the pointe shoes are more famous to the experts, but they do not work well for the beginners. The period for adapting shoes is needed for the dancers.

Table 6. Maximum Muscle Burden in slow motion (Unit: %).

		Bare Feet	Running Shoes	Pointe Shoes	Dance Sneakers
Thigh	Biceps femoris long head	103.9(3.6)	101.7(4.0)	104.6(5.0)	104.7(5.0)
	Biceps femoris short head	102.1(3.4)	102.0(3.9)	104.7(3.1)	103.8(1.4)
	Rectus femoris	100.5(3.7)	101.4(3.7)	105.7(2.5)	107.9(3.6)
Calf	Gastrocnemius medialis	99.9(2.2)	98.2(4.2)	106.3(5.7)	89.2(3.4)
	Gastrocnemius lateralis	100.7(2.6)	99.2(3.6)	104.0(3.0)	94.4(4.9)
	Soleus	117.8(6.2)	116.9(4.8)	114.4(4.7)	109.1(6.3)

Table 7. Maximum Muscle Burden in fact motion (Unit: %).

		Bare Feet	Running Shoes	Pointe Shoes	Dance Sneakers
Thigh	Biceps femoris long head	97.2(3.9)	99.5(5.6)	102.5(4.3)	100.2(2.2)
	Biceps femoris short head	103.7(3.8)	103.6(4.1)	102.3(4.1)	104.2(4.1)
	Rectus femoris	102.0(2.6)	101.3(4.8)	106.8(3.9)	107.3(6.3)
Calf	Gastrocnemius medialis	104.0(0.5)	93.7(2.4)	107.7(2.6)	99.9(3.4)
	Gastrocnemius lateralis	104.1(3.2)	98.2(4.8)	102.1(4.7)	96.8(3.3)
	Soleus	117.5(4.6)	116.8(4.8)	112.0(2.9)	109.4(2.2)

In the view of eccentricity and stability during pirouette, the effect of sneakers is obvious. The average and the standard deviation are shown in Table 8. Ballet shoes help the dancers to keep the rotating axis.

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Table 8. Sacral-Toe Distance (Unit: mm).

Shoes Type	Slow		Fast	
	Eccentricity	Stability	Eccentricity	Stability
Bare Feet	167.6 (6.4)	178.3(22.5)	181.4(5.9)	188.4(19.2)
Running Shoes	206.2(7.2)	137.3(21.0)	204.7(9.9)	151.7(44.9)
Pointe Shoes	201.7(12.2)	115.2(31.6)	210.6(8.8)	120.2(33.4)
Dance sneakers	193.1(4.4)	92.0(15.9)	212.2(6.7)	118.8(17.4)

4.2. Design Difference among the shoes

The main differences of analyzed shoes were the number of the shoe sole and shape around the ankle of the axis foot. Detail is shown in Table 9.

Table 9. Design difference among the shoes.

	Bare Feet	Running Shoes	Pointe Shoes	Dance sneakers
Number of a shoe sole	N/A	1	2	2
Protecting ankle design	X	O	X	O

In the view of the eccentricity, the performance of bare feet was the best. Any shoes could not help the novice users, because the free movement of foot muscles attributed that aspect. Dance sneakers were the second rank because two shoe soles were better than one for free movement of a foot. Thus we concluded that the number of shoe sole affected the stability during pirouette, two or more shoe soles are essential for ballet shoes.

In the aspect of the stability and muscle burden during rotation, the performance of dance sneakers was the first rank. That means ballet shoes can perform their own purposes. However, pointe shoes did not have better result than the running shoes, which was based on the shoe design around the ankle. As the posture of pirouette is difficult for beginners, the structure protecting the ankle can be effective.

4.3. The Direction of Design Optimization

The posture of standing with a toe is very difficult and unsafe for beginners, so design optimization of ballet shoes is essential and meaningful. This research implies the principal factors for ballet shoes. The one is permitting the muscle of the foot sole to move freely, and the other is protecting the ankle of the foot such as dance sneakers. Two or more shoe soles can help the free movement of the muscle of a foot sole, so the shoe sole shape considers the shape of the muscle of a foot [28]. The shape of a foot muscle, present design, and optimized design are shown in Figure17. Shoe soles are divided by the shape of the muscle.

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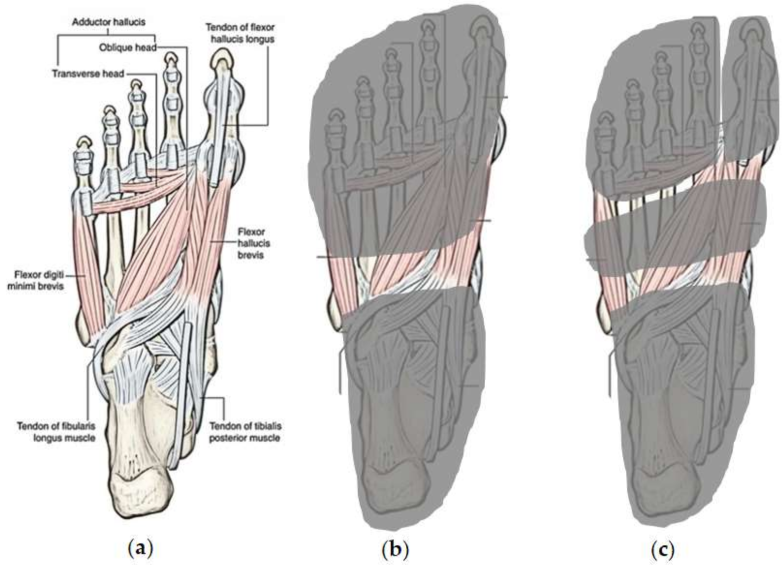

Figure 17. Foot muscles & Shoe sole design for ballet shoes (**a**) Muscle of the foot sole ;(**b**) Present shoe sole design of ballet shoes; (**c**) Optimal design of ballet shoes.

The further research which is the verification of the new concept ballet shoes and detail design optimization using the computer simulation with the musculoskeletal model will be performed after manufacturing the prototype of shoes.

5. Conclusion

Nowadays people are interested in diverse sports which could be difficult and dangerous for beginners such as ballet. Ballet shoes can help to improve the safety and performance, and they are verified using the qualified computer simulation with the musculoskeletal model, SIMM in this research. In the view of reducing the muscle burden and improving the stability during pirouette, dance sneakers are the best shoes for beginners. The design with divided shoe soles and protecting the ankle are main factors, and the direction for design optimization maximizes that factors. Consequentially the computer simulation with the musculoskeletal model can be applied to the design optimization of sports equipment and healthcare devices from a scientific viewpoint of biomechanics.

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