Investigating the relationship between frequency components of ground reaction force and sport shoe insoles comfort during stance phase of running

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ABSTRACT

Introduction: Shoe insoles are widely recommended to increase sport shoes comfort during running. However, relationship between ground reaction force frequency and perceived comfort is still unclear. The purpose of this study was to evaluate the relationship between ground reaction force frequency changes and perceived comfort during stance phase of running.

Methods: 30 female students (mean age of 22±1.85 year, height of 162±4.71cm and weight of 56±5.59 kg) were selected. Subjects were asked to run heel- toe in a control condition (only shoes) and three different insole conditions (soft, semi rigid, rigid). To assess perceived comfort, a questionnaire was completed by the subjects in four different insoles conditions. Vertical and anterior - posterior (AP) components of ground reaction force were evaluated in frequency domain using fast furrier transformation. Pearson's correlation coefficients was used to test relationship between the force frequency changes and perceived comfort ($P<0.05$).

Results: Findings showed that there was a significant negative relationship between perceived comfort and 99.5% frequency of vertical and AP ground reaction force ($r=-0.278$, $r=-0.239$ respectively), and median frequency of AP ground reaction force ($r=-0.229$).

Conclusion: Perceived comfort can be explained about 6% of variability in the 99.5% frequency power of vertical and AP ground reaction force and median frequency of AP ground reaction force.

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Introduction:

Insoles and foot protective equipment for decades have been considered and used. In many athletic skills such as running, because the human body is exposed to repeated impact forces that may cause injuries such as plantar fascia injury, fractures caused by fatigue, knee pain, patella femoral pain syndrome and etc for runners, athletes use insole to prevent injuries, increase comfort and improve performance (1-5). In addition, insoles and foot support means in many cases, such as patients with diabetes (6), correction of flat foot (7), moderate osteoarthritis of the knee (8) and the treatment of inflammation of the feet (9) are used as a therapeutic intervention. According to the applications, insoles and supportive devices are used for many different purposes, including the correction of skeletal (10), improvement of sensory feedback (11), increase comfort (3), reduction of muscle activity (12), reduce joint torque (13) and reduce the number of injuries (14).

One of the important factors that is used by physicians and designers of insole to determine fit of insoles is perceived comfort (3). Comfort is a factor that is understandable for people when use shoes or insoles and consider as an important aspect of insole and foot orthosis (3,4). Many studies have concluded that comfort is the most important factor for shoes in physical activities (15). Comfort has been reported with run, injuries, muscle activity, biomechanical factors, physiological or psychological related (16), as well as known as an important indicator for the proper function of the lower extremity and preventing or reducing the injuries associated with the motion (4).

Some of the factors that influence the comfort of insole and orthosis include shape of foot (15) the fit between shoes and feet (17,18), skeleton layout (19), plantar pressure (20,21), the sensitivity of the foot (4), forces acting on the musculoskeletal system, joint movement (22) and muscle activity (3). Forces acting on the musculoskeletal system can enter into a joint such as ground reaction force, so it can be concluded that previewed comfort can have relation with these forces.

Eslami and colleagues (2009) by investigating the effect of insoles on foot and perceived comfort in people with stalactites foot planter showed that insole condition significantly improved perceived comfort in the front, middle and rear in comparison with non-insole condition. In general, it can be concluded that improving perceived comfort of the mid-foot can be attributed to reduce oblique angle of heel in the sagittal page through the use of insole for people with stalactites foot planter (23). In another study, Milles et al (2011) reported and studied the effects of comfort and the motion of mid-foot in the case of useing 3 types of insoles, soft, medium and rigid on lower extremity function in patients with anterior knee pain that the soft insoles compared with the other 2 insoles were more comfortable, also foreign twin and flattened muscles activity in soft insole in which subjects were more comfortable was less than two other insoles (24).

As well as Jordan and Bartlett (1995) investigated plantar pressure distribution and perceived comfort in 3 kinds of shoes during walking in 15 men and stated that the increase in plantar pressure distribution may be associated with a reduction in the amount of comfort. The research findings suggest that measurement of plantar pressure distribution can be a useful tool to determine the causes of lack of comfort in the shoes (25).

To date, research on the effect of insole on comfort and its relationship with GRF has been limited and only a few studies have been done in this area which can note to the study of Manderman and colleagues (2003). They investigated the relationship between perceived comfort and peak points of GRF and the amount of loading in the case of using two types of molding and sloping insole (3). Results showed that molded insoles showed more comfortable feeling compared with the sloping insole and peak of GRF and amount of loading in molding insole was less than sloping insole, in fact, with increase of comfort of insole, these forces decreased. These results can prove the relationship between perceived comfortable and GRF. Also they stated that not only considered an important factor for shoe but also in terms of biomechanical is dependent on insole features. So investigating the relationship between perceived comfortable and biomechanical variables associated with harm, including GRF in the runners that use insole to quantify perceived comfortable and use it in the design of comfortable shoes and insoles to prevent injury and improve performance of runners instead of mental reports of individuals is important.

GRF during motion is considered a kind of input signal to the body that is received with different frequencies by mechanoreceptors in the skin and transmitted to the central- nervous system and responsiveness as frequency transmitted to the foot; on the other hand, foot sensitivity is associated with perceived comfort (4). So for a more detailed understanding of the relationship between GRF and perceived comfort, it is better in addition to taking into account the high point of GRF, its frequency be investigated. No study in the context of the relationship between the perceived comfort of insole and frequency of GRF is carried out, this study seeks to investigate the relationship between the difference in perceived comfort and changes in the frequency of GRF in response to the insole inside the shoe.

Methods:

In this study, 30 female students of Physical Education at Mazandaran University with mean age of 1.85±22 years, height 4.71±162 cm and a weight of 5.59±56 kg were selected. Participants had no abnormalities in the lower extremity and at the time of testing these people not had any lower extremity injury such as damage to ligaments specially the anterior cruciate, sprains, tendon and muscle injuries such as strains and muscle and tendon tears bone damages such as fracture and stress fracture and any surgery in lower extremity joints during the past 12 months and were completely healthy. This study was quasi-experimental and field and sampling method was easy or available. All of the subjects registered their personal information in a form that was given to them before running test and they were assured that this information is confidential.

In this study, three types of insole with the same shape and different compound (rigid) materials, respectively, soft, semi-rigid and rigid insole was used. The insoles were prefabricated and their length was equal to length of foot. Thick of foams forming insoles was soft, semi-rigid and rigid foam of 5 mm, thick of polypropylene (P.P) 1.5-2 mm, and rigid foam was 7mm. Also generally thick of insoles under the heel 6 to 10 mm and in the center of medial longitudinal arch reaches to 25 to 30 mm. The feature related to each insole is reported in Table 1.

Shoe insole of control group was standard insole of shoe of test. The shoe style of samples were the same, in fact, to eliminate confounding shoe, a shoe that was used for sampling was two pairs of the same sport shoes with two different sizes fit with the size of foot of the subjects. Testing in Biomechanics Laboratory of Faculty of Physical Education and Sport Sciences at the University of Mazandaran was conducted and so the test place was the same for all participants. In this study, subjects performed five tests. The first test was conducted with shoes without insoles (control condition) and next tests were conducted by putting insoles (soft, semi-rigid and rigid insoles) in shoes. How to run the test was this that after preheating, the subjects were asked to stand in the determined distance from the dynamometer board that was in running track and in such a way steps that they across with the right foot over the dynamometer board. Running track was 25 m and dynamometer plate was placed at a distance of 15 meters from the starting point. The dynamometer plate (Manufacturer: Kistler model winterthor, sampling rate: 1000 Hz, made in Switzerland, 2009) was used to measure data related to ground reaction force. The device has a width of 40 cm and length of 60 cm and was embedded in a convenient location so that participants are not able to recognize it. Calibration of force plate based on the factory assumptions with the power of 1000 Hz sampling was used. Stepping method of subjects was as heel - toe, with detaching right foot from the dynamometer board, the test was completed.

Metronome was used to control the speed of subjects. As well as to collect information related to subjects shoe insole comfort, Visual Analog Scale was used. The scale provides a valid size for assessing perception of comfort (3,4,23,27,26), and contains nine questions contain information such as the perceived comfort in the forefoot, arch, heel, etc. that for each question is intended classification of 0 to 15. Score 0 shows lack of comfort and score of 15 showed the highest comfort. It should be noted that for each insole, a separate questionnaire in the listed form was given to subjects to report feel of comfortable in 4 modes only shoe without insole, shoe plus soft insole, shoe plus semi-rigid insole and shoe plus rigid insole by the questionnaire. When gathering data of force by dynamometer board, the subjects were not allowed to touch the insole with hand. As about the type of insoles, a description was not given to participants to ensure that visual and sensory feedback not affect how stepping of subjects and classification of comfort, in addition, since the order of evaluation of perceived comfort of insole was important by subject and could affect perceived comfort, for example, if semi-rigid insole was evaluated after rigid insole, might be considered as a soft insole by subject, so the order of evaluating perceived comfort was completely controlled. In this case, first condition of shoes was evaluated and then soft, semi-rigid and rigid insole was evaluated and subjects were not aware in any way of the arrangement of insoles. Each individual tested 5 times and the mean of five tests were used for statistical analysis. After running each test, the individual was asked to fill questionnaires on perceived comfort of insole as well.

GRF data was collected by the dynamometer board, first using the technique of Butterworth grade 4 with shear frequency of 50 were filtered (28), and then to calculate variables, filtered data were used. In order to investigate the frequency of GRF, it was needed to this signal from the time function converts to the frequency function. Converting alternating signals to the equivalents of frequency is called Fourier transform or harmonic analysis. In fact, Fourier transform measures the amount of movement that occurs at any frequency as a result, a series of different frequencies is occurred that as power spectrum is known (29).

For this purpose, after filtering data of GRF (vertical and anterior-posterior) that was obtained by dynamometer board and it was in the time function, it is according to formula 1 and using MATLAB software 2008 edition from the time function turned to the frequency function (Figure 1).

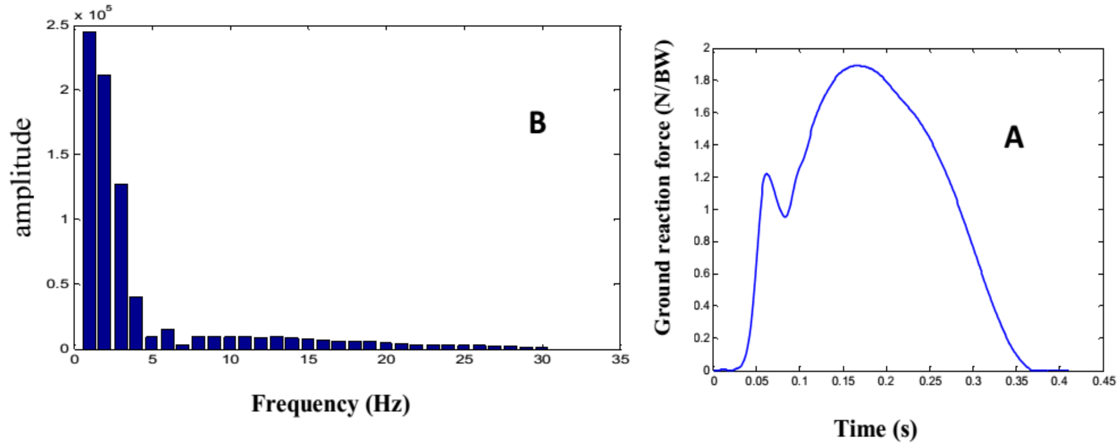

Figure 1. A. Ground reaction force in time domain and B. Power spectrum of ground reaction force signal in frequency domain for a subject during heel-toe running

Table 1. Characteristics of insoles used in this study

	First layer (in the vicinity of the foot)	Second layer	Third layer	Fourth layer
Soft insole	Soft foam	Polypropylene	Bone poly foam	Rigied poly foam
Semi-rigid insole	Semi-rigid foam	Polyoropylene (P.P)	Bone poly foam	Rigied poly foam
Rigid insole	Rigid foam	Polypropylene (P.P)	Bone poly foam	Rigied poly foam

Discrete spectral of frequency content is determined as multiple from the frequency of basis that any of them is called harmonic that with the sum of n harmonic is equal to: (30).

Formula 1

$$F(t) = \sum AnSin(n\omega_0 t + \theta n)$$

An = amplitude, $\omega 0$ = base frequency, n = harmonic coefficients, θn = the phase angle

After the calculation of the input signal frequency (GRF), three indexes of frequency using three methods were used (31,32). The first indicator: frequency with power of 99.5% (F99/5%), which indicates the frequency that has 99.5% signal power or, in other words 99.5% of signal power is lower than that frequency and calculation formula is as follows (formula 2), that P calculated power as the integral of frequency signal against amplitude and *f*max is the maximum frequency of signal. The second indicator of median frequency is (Fmed) that occurs at the point where half the signal power is above and half is below it (Formula 3). In various studies, it is assumed, when the body enters force to the ground, the frequency median of GRF can represent performance of swinging components of neuro-motor system. The third indicator is frequency bandwidth (Fband) that is the difference between maximum frequency and minimum frequency when the signal power is in a point greater than half the maximum signal power (Formula 4). The index may show the need of the motor units.

Formula 2

$$\int_0^{f_{99.5}} P(f)df = 0.995x\int_0^{f_{\max}} P(f)df$$

$$\int_0^{f_{med}} P(f)df = \int_{f_{med}}^{f_{max}} P(f)df$$

Formula 3

$$f_{\text{band}} = f_{\max} - f_{\min} (\text{when } P > 0.5xP_{\max})$$

Formula 4

After collecting raw data, descriptive statistics for classifying data and determining the central indicators and dispersion as well as to estimate the significance of the relationship between shoe insole comfort and frequency indicators GRF, Pearson correlation coefficient was used. Data were analyzed using SPSS 18. The statistical significance was set at $0.05 \geq P$.

Results:

General characteristics of subjects are shown in Table 2.

Table 2. Demographic characteristics of subjects

Subjects	N=30
Mean of heigh (cm)	4.71±162
Mean of age (year)	1.85±22
Mean of weight (kg)	5.59±56

The mean values and standard deviation of GRF frequency during stance phase of running in two directions, vertical and anterior-posterior and also values related to mean and standard deviation of perceived comfort of insole are shown in Table 3 and Table 4.

The statistical results showed that the differences in the perceived comfort between rigid and semi-rigid insole compared with control condition and soft insole was more than one point of comfort and was statistically significant ($P<0.001$), as the mean value of perceived comfort in rigid insole conditions 3.45 points (29.19%) and semi-rigid insole 3.20 points (27.06%) was more than the mean value of perceived comfort in the non-insole conditions. On the other hand, the mean value of perceived comfort in rigid insole conditions 5.08 points (42.14%) and semi-rigid insole 4.83 points (40.91%) was more compared with the mean value of perceived comfort in soft insole conditions. It was also observed soft insole had the lowest mean of perceived comfort with 6.98 points and rigid insole had the most mean of perceived comfort with 12.07 points among the subjects (Figure 2).

In other words, rigid insole compared to control conditions and in comparison with other studied insoles showed a higher perceived comfort. Statistical test of Pearson's correlation showed that the perceived comfort of insole had significantly relationship with frequency with power of 99.5% GRF vertical and anterior-posterior (respectively $P=0.039$ and $P=0.016$) that the correlation was negative, ie, by increasing perceived comfort of insole, the frequency with the power of 99.5% GRF of vertical and anterior-posterior reduces.

Also the relationship between perceived comfort and frequency median GRF of anterior-posterior was also statistically significant and negative ($P=0.048$). The relationship between perceived comfort and frequency band of GRF (vertical and anterior-posterior) and mid-frequency of vertical GRF was not statistically significant ($P>0.05$) (Table 5).

Table 3. Mean and standard deviation of the frequency of vertical and anterior-posterior GRF

	Frequency with power of 99.5% GRF (Hz)		Frequency medium GRF (Hz)		Frequency bandwidth GRF (Hz)	
	±SD Mean (vertical)	±SD Mean (Anterior-posterior)	±SD Mean (vertical)	±SD Mean (Anterior-posterior)	±SD Mean (vertical)	±SD Mean (Anterior-posterior)
Shoes (control)	14.93±2.25	15.13±3.41	2.01±0.61	2.98±0.66	1.27±0.55	2.66±0.89
Soft insole	14.26±1.79	13.33±4.23	2.03±0.56	3.00±0.50	1.19±0.23	2.40±0.73
Semi-rigid insole	13.06±2.08	12.63±3.28	1.65±0.38	2.90±0.60	1.16±0.23	2.66±0.89
Rigid insole	11.46±2.44	11.40±2.13	1.79±0.59	2.40±0.48	1.12±0.21	2.33±0.61

Table 4. Mean and standard deviation of perceived comfort of insole

Type of insole	Shoe insole comfort
Shoes (control)	8.62±3.32
Soft insole	6.98±3.27
Semi-rigid insole	11.82±1.83
Rigid insole	12.07±2.88

Table 5. Lists of coefficients of the relationship between the frequency of GRF and the perceived comfort of insole

	Correlation (r)	Significant level (p)
$F_{99.5\%}$ GRF vertical	-0.278	0.016*
$F_{99.5\%}$ GRF anterior-posterior	-0.239	0.039*
$F_{99.5\%}$ GRF vertical	-0.109	0.352
$F_{99.5\%}$ GRF anterior-posterior	-0.229	0.048*
$F_{99.5\%}$ GRF vertical	-0.062	0.597
$F_{99.5\%}$ GRF anterior-posterior	-0.087	0.458

* The value of statistical significance at the 0.05 level

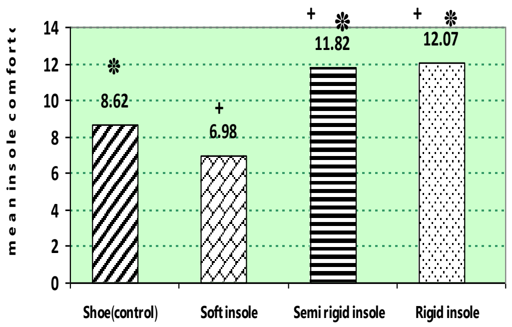

Figure 2. Mean insole comfort in various insole condition (*significantly as compared with the control condition and + significantly as compared with the soft insole condition)

Conclusion:

The aim of this study was to investigate the relationship between vertical and anterior-posterior GRF frequency and perceived comfort of insole. Based on the results of this study, the use of insole was effective in improving comfort of shoes that is consistent with the study of Yang Hee and Visin (2005), Manderman and colleagues (2001,2003) and Eslami and colleagues (2009) in this regard. Rigid insole in terms of comfort was significantly greater than the control conditions. However, a number of subjects considered semi-rigid insole or control mode that was without insole more comfortable. Totally subjects considered all tested insoles except soft insole compared to the control condition more comfortable that with Manderman study (2001) was in line (4).

In fact, soft insole conditions had lower perceived comfort compared with other findings that was inconsistent with findings of Manderman (2002) and Mills et al. (2011) (24,26).

The reason of inconsistency of these findings with the results of this study may be due to a different type of insole. Also subjects were people who had knee injury while subjects in the study, including healthy people and in terms of sole were normal. In general, the results of this study show that the perceived comfort can probably affect by wearing different running shoes insoles (from type). These findings support the results of recent studies on the ability to recognize people in understanding the differences of different insoles (21).

In fact, the results shows that different people may have different perceived comfort based on different type of insole and insole type can be considered an important factor in perceived comfort. Small difference in the perceived comfort between rigid and semi-rigid insole may be due to the approximate similarity of made materials in top layer of two insoles. Stated subject's reaction to insoles affects various factors, including biomechanical factors (35), neuro-physiological (20) anatomic and perhaps even psychological factors so many different subjects use different strategies in response to the insole. The researchers also related perceived comfort of the insole and orthotics with other factors including plantar pressure, sensitivity of foot and legs and feet layout (20,5).

So that the possible reason that can note for the difference in perceived comfort between the different insoles by the subjects is that every individual has a threshold of triggering pressure on his foot.

Also according to the findings, the relationship between frequency with power of 99.5% GRF in vertical and anterior-posterior and frequency median of GRF in anterior-posterior and perceived comfort was significant so that increasing comfort of insole was associated with reducing the indicators of force-frequency. The result was consistent with the study results of Manderman et al (2003) that investigated the relationship between kinetic variables (contact force and loading rate) and perceived comfort of insole in 21 subjects with flat sole during running (3).

They observed that there is a significant relationship between these variables and perceived comfort so that by increasing perceived comfort, contact force and loading was reduced. Also Yang Hee and Visin (2005) by investigating the effects of shoe insole and heel height on plantar pressure, contact force and perceived comfort observed perceived comfort of insole had significantly relationship with contact force (0.369r = -) and the peak of pressure in the forefoot (= -0.369) that is consistent with the results of current study ($P<0.01$) (27).

In general, according to research results, the characteristic and type of insole may affect the frequency of the input signal to the body that is detected through sensory system of the body. However, the difference in the input signal was caused a difference in the perceived comfort between different conditions of insole. If the shoe is not comfortable, the load on the muscles and joints increases and muscles to control and reduce the load even more acts that will lead to early fatigue. Previous studies have reported that long thin muscle fatigue causes to reduce balance of foot (33) and anterior tibialis muscle fatigue causes running damages such as fracture due to pressure (34).

Thus, according to the results, differences in the perceived comfort and its communication with the power frequency change can be probably related to predict and prevent running injuries. Thus it can be concluded that the more the perceived comfort of insole is greater, may be the chance of injury during exercise such as running reduced. The results of this study in order to confirm the results of the study of Manderman (2001) and Gross and colleagues (1991) showed that injury frequency rate has decreased with increasing perceived comfort of shoes (35,4).

Overall, this study showed that there is a relationship between increasing perceived comfort of insole and reducing the frequency with power of 99.5% GRF in vertical and anterior - posterior and frequency median of GRF in the anterior - posterior, that these relations respectively with 7.7%, 5.6%, 5.2% variances overlap that shows although this relationship is weak but is not zero. Accordingly can say differences in the perceived comfort of insole may be described in part by changing the frequency of force.

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بررسی ارتباط بین مؤلفه‌های فرکانسی نیروی عکس‌العمل زمین و درک راحتی کفی کفش ورزشی در فاز اتکاء دویدن

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چکیده

مقدمه: کفی‌های کفش به طور گسترده برای افزایش درک راحتی کفش ورزشی طی دویدن توصیه می‌شوند. با وجود این، ارتباط بین فرکانس نیروی عکس‌العمل زمین و درک راحتی هنوز مبهم است. هدف تحقیق حاضر، ارزیابی ارتباط بین تغییرات فرکانسی نیروی عکس‌العمل زمین و درک راحتی در فاز اتکاء دویدن بود.

روش کار: ۳۰ دانشجوی دختر با میانگین سن ۱/۸۵±۲۲سال، قد ۴/۷۱±۱۶۲سانتیمتر و وزن ۵/۵۹±۵۶ کیلوگرم انتخاب شدند. از هر فرد خواسته شد در شرایط کنترل (فقط کفش) و ۳ شرایط کفی (نرم، نیمه سخت، سخت) به صورت پاشنه - پنجه روی صفحه‌ی نیروسنج بدوند. جهت ارزیابی میزان درک راحتی، پرسشنامه‌ای توسط آزمودنی‌ها در ۴ شرایط مختلف کفی تکمیل شد. مولفه‌های عمودی و قدامی - خلفی نیروی عکس‌العمل زمین در تابع فرکانس با استفاده از تبدیل فوریر محاسبه شد. همبستگی پیرسون برای آزمون ارتباط بین تغییرات فرکانس نیرو و درک راحتی استفاده شد ($P<۰/۰۵$).

نتایج: نتایج نشان داد رابطه معنی‌دار و منفی بین درک راحتی کفی و فرکانس با توان ۹۹/۵ درصد نیروی عکس‌العمل زمین عمودی و قدامی - خلفی (به ترتیب $P=۰/۰۱۶$ و $P=۰/۰۳۹$) و میانه فرکانس نیروی عکس‌العمل زمین قدامی - خلفی وجود دارد ($P=۰/۰۴۸$).

نتیجه‌گیری: تقریباً با ۶ درصد هم‌پوشانی واریانس‌ها، درک راحتی ممکن است از طریق فرکانس با توان ۹۹/۵ درصد نیروی عکس‌العمل زمین عمودی و قدامی - خلفی و میانه فرکانس نیروی عکس‌العمل زمین قدامی - خلفی تفسیر شود.

کلیدواژه‌ها: فرکانس، درک راحتی، نیروی عکس‌العمل زمین

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