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Evaluation of Muscle Fatigue Based on Detection of Three-Dimensional Center of Gravity

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ABSTRACT: Detection of the Three-Dimensional Center of Gravity theory, abbreviated as D3DCG, is a research method invented by the second author to detect the position of the center of gravity (COG) of objects and their risk of tipping. Originally, D3DCG was devised to avoid overturning accidents when transporting containers by trailer. This theory has since been applied to container trucks, ships, and drones, and to human COG detection and fatigue evaluation. In terms of evaluating human fatigue, D3DCG has widely various practical applications in fatigue measurement using the ratio of lateral force denoted as q to critical lateral force denoted as q_{max}. This study specifically examines muscle fatigue measurement and verification of the accuracy of the ratio of the COG height, designated as l to the maximum COG height denoted as $l_{\max}$, which is expressed as $l/l_{\max}$. This study measured the vertical and horizontal motion frequencies of a human body during the three states associated with passage through a pedestrian overpass, including ascending stairs, flat top pass, and descending stairs, after experiencing long hours of hard cooking tasks while maintaining uncomfortable postures. We calculated the height of the human body's COG using D3DCG, demonstrating and verifying that the $l/l_{\max}$ indicator can assess human muscle fatigue effectively.
KEYWORDS: D3DCG; fall risk; human muscle fatigue; $l/l_{\max}$; muscle fatigue evaluation.

I. INTRODUCTION

To prevent work accidents caused by fatigue, real-time fatigue monitoring of individuals is necessary. Detection of the Three-Dimensional Center of Gravity theory (D3DCG) is applied to the human body to monitor fatigue. Based on the frequency of oscillation, D3DCG calculates the position of the center of gravity (COG) of a moving object. Human walking fatigue is evaluated and analyzed by monitoring the frequency of swaying when people walk. The findings can then be used to calculate the position of the body. The human body data obtained using this method are of great importance for real-time analysis of fatigue.

Watanabe (2011) invented the D3DCG research method to detect the position of the COG of objects and their risk of tipping. This research method presents benefits of low cost, good effectiveness, and the ability to monitor the COG of objects in real time. The innovation of D3DCG for preventing moving objects from tipping over lies in its ability to detect the COG of a moving object even when the weight (m) and spring rebound rate (k) of the object are unknown.

Initially, D3DCG was created from the concept of motion dynamics of a ship floating on water. During its development and increasing application, it has been found to be useful for work in various fields. Kawashima et al. (2011) studied the application of D3DCG in the field of railway transportation and realized three-dimensional positioning of the COG of a train with D3DCG, proving that D3DCG is a safe technology that can be installed flexibly on a train to detect the train's COG at low cost. Furthermore, Kawashima et al. (2013) applied the D3DCG theory to detect aging degradation of train springs, thereby saving costs of factory inspections of trains. Dang et al. (2016) studied the application of D3DCG to the COG detection of shipping container trucks. Because shipping container cargos include widely various goods and because their internal placement status is uncertain, D3DCG can resolve associated difficulties well. Dang proved that it is not a heavier cargo that causes a shipping container truck to tip over: a container with a higher COG is more likely to cause the truck to tip over. Xu et al. (2023) studied the application of D3DCG to detect the stability of the COG when drones deliver medicines. To date, D3DCG has been verified and applied to assess aspects of sea transportation, land transportation, and air transportation.

The D3DCG theory is also applicable to the human body. Kohinata et al. (2020) used D3DCG to analyze a human body in motion, ascertaining the COG according to the frequency of heaving and rolling during walking. They investigated the walking patterns of different age and gender groups on smooth and rough surfaces. Subsequently, Watanabe and Yagiura et al. studied the application of D3DCG for the detection of human fatigue and heat stroke. They launched a new experimental device for real-time monitoring. Song applied D3DCG to the detection of muscle fatigue during climbing. Hasegawa applied the fatigue evaluation index of D3DCG to marathon running. The fatigue evaluation indicators used for those three studies are all ratios of lateral force q to critical lateral force q_{max} (q/q_{max}). Therefore, q/q_{max} has been found to be an indicator reflecting human posture that is affected by fatigue.

Furthermore, D3DCG has been shown to be very rich for analyses. The ratio of the height of the COG l to the maximum height of the COG $l_{\max}$ ($l/l_{\max}$) is also a fundamentally important indicator for assessing the risk of an object toppling because of human muscle fatigue. However, in studies described previously, researchers have not achieved important achievements in the field of human muscle fatigue as an indicator of $l/l_{\max}$. For the present study, the author verified the feasibility and correctness of the $l/l_{\max}$ index in human muscle fatigue through experimentation.

II. METHODOLOGY

2.1. Derivation of the basic formula for Detection of the Three-Dimensional Center of Gravity theory (D3DCG)

The following formula is useful for the deriving the basic formula of Detection of the Three-Dimensional Center of Gravity theory (D3DCG):

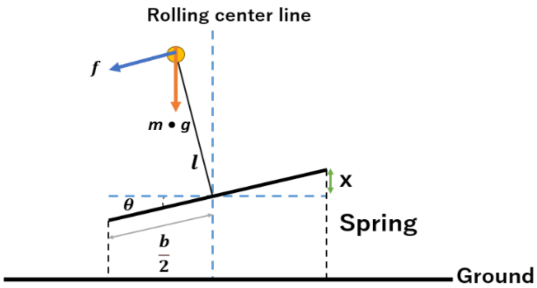

Figure 2.1: Simplified schematic diagram of the model.

In D3DCG, we consider the part that supports an object as a spring structure, such as the tires of trucks and the muscles of the human body.

According to the formula of harmonic motion, the following can be inferred.

$$T' = 2\pi\sqrt{\frac{m}{2k}} \quad (1)$$

For that equation, the following variables are used.

T': Single vibration period of the vehicle in the vertical direction

k: Spring constants on the left and right sides of the vehicle

m: Weight

π: Pi

The rolling of an object moves around the axis of the vehicle in which the COG is located. Its occurrence is attributable to the gravitational moment caused by the anti-gravity of the spring. Because the rolling moment and restoring force of an object are equal, the following can be derived.

$$\begin{aligned} lf &= -kx\frac{b}{2} + mgl\sin\theta - kx\frac{b}{2} \\ &= -kxb + mgl\sin\theta \quad (2) \end{aligned}$$

The following variables are used in that equation.

f: Force towards COG tangent

θ : Roll angle

l : Height of the COG from the rolling axis

b: Length between springs

x: Vertical deviation of each spring

As shown in Figure 2.1,

$$x = \frac{b}{2}\sin\theta \quad (3)$$

Then,

$$f = -\frac{m}{l}\left(\frac{kb^2}{2m} - gl\right)\sin\theta \quad (4)$$

According to the trigonometric formula, if θ is sufficiently small, then sin θ can be rewritten as θ. The lateral force f is equivalent to the tangential force of circular motion with radius l .

$$ml\frac{d^2\theta}{dt} = f = -\frac{m}{l}\left(\frac{kb^2}{2m} - gl\right)\theta \quad (5)$$

Also, θ is defined as the ω phase:

$$\omega = \frac{1}{l}\sqrt{\frac{kb^2}{2m} - gl} \quad (6)$$

Defining the frequency of heaving as v' and rolling as v, then the frequency is inversely proportional to the period, which is obtainable as shown below.

$$v' = \frac{1}{T'} = \frac{1}{2\pi}\sqrt{\frac{2k}{m}} \quad (7)$$

$$v = \frac{1}{T} = \frac{\sqrt{\frac{kb^2}{2m} - gl}}{2\pi l} \quad (8)$$

From these equations, a quadratic equation is obtainable for the height of the COG l, where the values of g and π are fixed. Also, b is measurable. The values of v and v' can be determined by the motion sensor. Therefore, even if the weight or spring constant is unknown, it can still be calculated.

$$l^2 + \frac{g}{4\pi^2 v^2} l - \frac{b^2 v'^2}{4v^2} = 0 \quad (9)$$

When an object does not roll over, the direction of the restoring torque is opposite to the direction of the gravitational torque.

$$\frac{kb^2}{2m} - gl > 0 \quad (10)$$

Under critical conditions, the formula for is obtainable as shown below.

$$l_{max} = \frac{\pi^2 v'^2 b}{g} \quad (11)$$

2.2 Application of D3DCG in the human body

For D3DCG application to the human body, as shown in Figure 2.2, the human body has three COG positions as the head (C), chest (B), and abdomen (A) because the neck, abdomen, and legs of a person are equivalent to three springs which provide support for the upper part of the body. The key point of gravity which determines whether the entire human body will tilt is COG (A) of the abdomen: a pedestal structure with the pelvic plane as the reference, the legs as the support, and the abdomen as the main body.

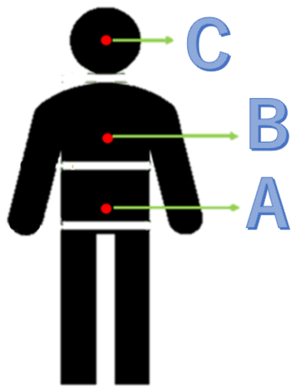

Figure 2.2: Schematic diagram of the human COG.

It is particularly interesting that human walking is a forward movement based on alternate motion of the feet. Therefore, its Fourier Fast Transform (FFT) image shows regular variation of arithmetic sequences.

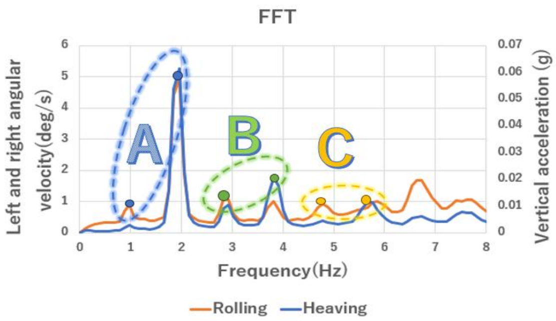

Figure 2.3: Relations among the three COGs of a human and the combination of peak frequencies obtained in FFT.

2.3 Evaluation indicators for human muscle fatigue ($l/l_{\max}$)

Because $l_{\max}$ stands for the maximum COG height of the object's tipping boundary, l expresses the current height of the object's COG. That is to say, if $l \geq l_{\max}$ occurs, then the object will flip or tilt. Therefore, as l gradually approaches $l_{\max}$, the ratio of $l/l_{\max}$ approaches 1, representing a higher risk of an object overturning or tilting.

Similarly, when $l_{\max}$ gradually approaches l , the closer the ratio of $l/l_{\max}$ is to 1, meaning that the human body is more prone to falling. Greater instability demonstrates that the muscles are more fatigued.

Next, the accuracy of this indicator as an evaluation index for human–machine muscle fatigue is verified by experimentation.

III. EMPIRICAL EXPERIMENT

To verify the accuracy of this indicator as an evaluative index for human muscle fatigue, the author conducted the experiments described below.

Physical condition of the experiment subject

-Age and sex: 23-year-old woman

-Weekly exercise frequency: Hardly ever

State of the experiment causing fatigue

-Type of hard work: hours of cooking with a stooped posture

-Date and hours: 01/01/2024, 5 h (15:00–20:00)

The experiment subject experienced 5 h of hard work cooking while maintaining an uneasy posture, causing fatigue and soreness in the leg muscles as presented in Figure 3.1.

The cooking experiment is intended to make muscles tired and to accumulate fatigue in the legs.

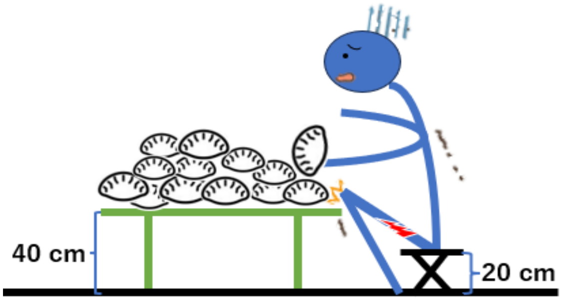

Figure 3.1: Hours of hard work cooking while maintaining an uneasy posture.

Experimental device for measuring heaving and rolling

As shown in Figure 3.2, the experiment setup is a portable waist belt sensor that consists of a waist belt and a motion sensor. This device for experimentation presents benefits of portability, allowing for maximum measurement of human movement data within the minimum limit of human movement restrictions.

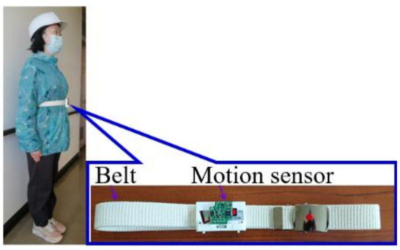

Figure 3.2: Experimental device for measuring heaving and rolling.

Table 3.1: Relevant parameters of the sensor used for experimentation.

Motion sensor	WitMotion SDCL
Acceleration range	±4 g
Angular velocity range	±500 deg/s
Storage	SD card
Power	internal battery
Duration	48 h

Experiment location for the fatigue measurements

To demonstrate the usefulness of $l/l_{\max}$, walking experiments were conducted over a pedestrian overpass near the home of the first author in Tokyo. Walking over it is difficult because the legs have accumulated muscle fatigue after the hard work.

Walking over the pedestrian overpass is done to test how well D3DCG can evaluate muscle fatigue.

Figure 3.3: Experiment location for fatigue measurements.

Experiment steps

-The experiment subject wears the portable belt sensor to detect human COG.

-The experiment subject passes via a pedestrian overpass

The experiment subject conducted walking on the first day (24 h later), second day (48 h later), and third day (72 h later) after muscle fatigue was caused by hard work. During walking, data from the sensor and the states of the experiment subject were recorded. The analyses for the measured data were conducted respectively under three conditions: ascending the overpass stairs, crossing the flat top, and descending stairs of the other side of the overpass. $l/l_{\max}$ was calculated for each of the three measurements.

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IV. FREQUENCY ANALYSIS AND RESULTS

The experiment subject's vertical acceleration and horizontal angular velocity can be measured by the sensors carried by the experimental device. A raw dataset of heaving and rolling measured by the sensor is presented in Figure 4.1.

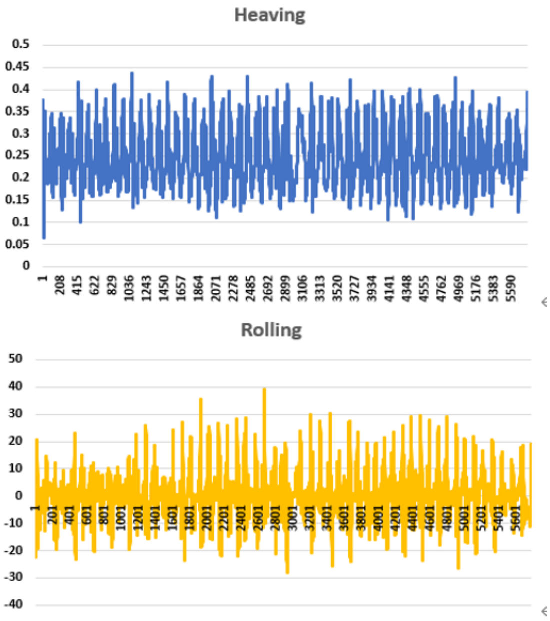
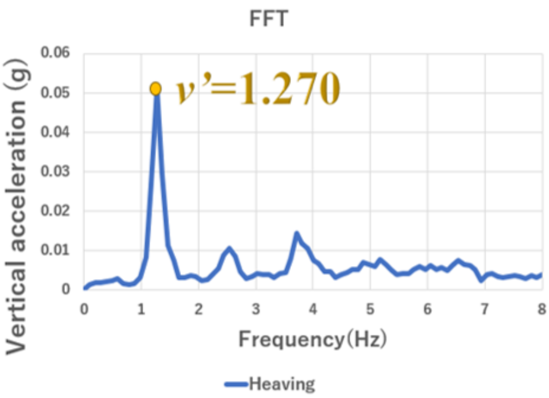


Figure 4.1: Raw dataset of heaving and rolling measured by the sensor.

By performing Fast Fourier Transform (FFT) on the obtained data, frequency v corresponding to rolling and frequency v' corresponding to heaving is obtainable as shown in Figure 4.2 and Figure 4.3. Then $l/l_{\max}$ is calculable by substituting it into equations (9) and (11).



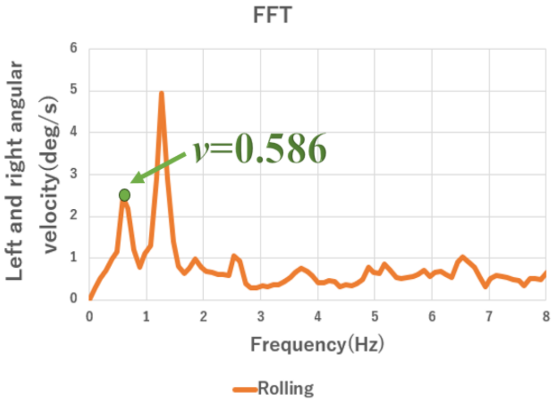


Figure 4.2: Set of v' and v obtained through FFT from experiment data analysis (Day 1 of ascending the stairs).

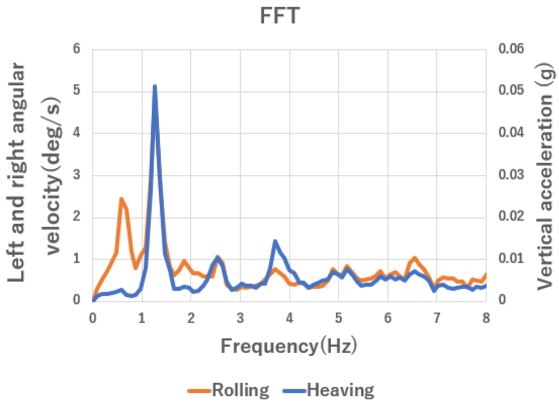


Figure 4.3: Selection between v' and v by overlaying the heaving and the rolling in FFT (Day 1 of ascending the stairs).

The heaving and the rolling data of the experiment subject on the first day (24 h later), the second day (48 h later), and the third day (72 h later) after being affected from muscle fatigue were analyzed. The overall collected data were divided into three states: ascending the stairs, crossing the flat top, and descending the stairs. These experimentally obtained data were analyzed separately. Tables 4.1, 4.2, and 4.3 show the results of D3DCG for the three states. Among them, Day 1 represents the experimentally obtained results on the second day after the hard work, the first day when muscles felt sore, which was 24 h later. The same goes for Day 2 and Day 3. "Ascending the stairs" presents the results obtained when ascending the stairs. "Crossing the flat top" presents the results of crossing the flat top of the overpass. Also, "Descending the stairs" presents the results of descending the stairs.

Table 4.1: Results of D3DCG ascending the stairs of the overpass.

Ascending the stairs	Day 1 (24 h)	Day 2 (48 h)	Day 3 (72 h)
v	0.586	0.781	0.879
v'	1.270	1.563	1.660
l	0.066	0.089	0.095
l_{max}	0.072	0.108	0.122
l / l_{max}	0.917	0.821	0.773

Table 4.2: Results of D3DCG crossing the flat top of the overpass.

Crossing the flat top	Day 1 (24 h)	Day 2 (48 h)	Day 3 (72 h)
v	0.879	0.977	1.074
v'	1.758	1.855	1.953
l	0.104	0.108	0.112
l_{max}	0.137	0.153	0.169
l / l_{max}	0.756	0.707	0.659

Table 4.3: Results of D3DCG descending the stairs of the overpass.

Descending the stairs	Day 1 (24 h)	Day 2 (48 h)	Day 3 (72 h)
v	0.586	0.781	0.879
v'	1.660	1.953	1.953
l	0.107	0.129	0.123
l_{max}	0.122	0.169	0.169
l / l_{max}	0.872	0.760	0.724

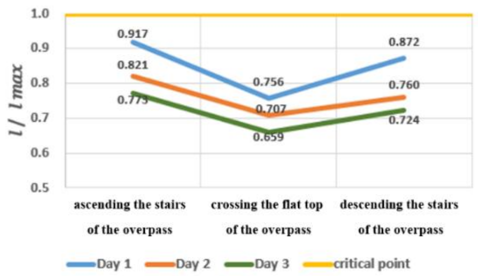


Figure 4.4: Transition of l/l_{max} in the three conditions: ascending the stairs, crossing the flat top, and descending the stairs.

Subjective feelings of the experiment subject are presented in Table 4.4.

Table 4.4: Subjective perceptions reported by the experiment subject:

	Day 1 (24 h)	Day 2 (48 h)	Day 3 (72 h)
Subjective feelings of the subject	Muscle tension, pain when walking, intense pain when walking on stairs	Muscle soreness, with almost no change in pain compared to the previous day.	The pain has been relieved. Pain during walking has disappeared.

Taking the time of day as a measure, the value of l/l_{max} in Figure 4.4 generally shows a downward trend with days, which is related to the subsidence and relief of pain. Comparing the subjective feelings of the experiment subject in Table 4.4, this finding seems reasonable. Therefore, l/l_{max} is an effective indicator for evaluating human muscle fatigue.

Based on differences in walking conditions under the same muscle state on the same day as the evaluation criterion, a numerical relation can be found between l/l_{max} of the three conditions: Ascending the stairs > Descending the stairs > Crossing the flat top. Especially on the first day (24 h), the l/l_{max} on ascending the stairs was as high as 0.92.

When people are in good physical condition, they often think that they are more likely to feel tired when ascending stairs than when going downstairs because they must overcome gravity and do work when ascending stairs. The reason for the large l/l_{max} ratio during the ascent phase is that it requires overcoming of gravity to do work. During the process of ascending stairs, it is unstable to have one foot on top of a step, which is the support. Only one foot is subjected to force at this time. Therefore, the ratio associated with ascending the stairs is greater than the ratio when descending the stairs. As a result, from this perspective, l/l_{max} can evaluate the stability of the human body effectively.

By observing the change of l/l_{max} on the three days under the three walking conditions in Figure 4.4, the pain on Day 1 is the most readily apparent as shown by comparison to the feelings presented in Table 4.4. The difference between l/l_{max} on Day 1 and l/l_{max} on Day 2 is much greater than the difference between l/l_{max} on Day 2 and l/l_{max} on Day 3, especially when ascending and descending the stairs.

Based on these results, it can be understood that a day's delayed onset of muscle soreness after hard work cooking has a strong effect on the human body when ascending and descending stairs. In the middle walking state of the flat top, the difference among the three days' experiment results was not as readily apparent as ascending and descending stairs. Based on these dimensional analyses, it can also be inferred that l/l_{max} can evaluate human muscle fatigue effectively.

In summary, l/l_{max} is useful as an index for evaluating human muscle fatigue and stability.

V. CONCLUSION

Through the analysis presented in Chapter IV, the author has demonstrated from three-dimensional analysis that l/l_{max} is useful as an evaluation index for human muscle fatigue and stability. Because the rest time is longer, muscle fatigue decreases as l/l_{max} decreased.

When the muscles are in the same state, the change in human stability across the three states is the following: Ascending the stairs > Descending the stairs > Crossing the flat top. The results of l/l_{max} obtained from the three states are consistent with this finding. The effects of muscle fatigue on human stability are more pronounced on stair states than when crossing the flat top of the pedestrian overpass. Changes in l/l_{max} obtained from the experiment follow this pattern. Therefore, l/l_{max} is an effective index for evaluating human muscle fatigue.

This study once again validates D3DCG for the detection of human muscle fatigue and fall prevention. This research not only expands the applicability of D3DCG: it also provides a new fatigue detection index for researchers studying human muscle fatigue.

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