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Analysis of the Area of Center of Pressure (COP) Trajectories According to Running Speed and Its Correlation with Ankle Joint Motion

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Objective: The purpose of this study was to determine the difference of motions using the new calculation method of COP area and to investigate the correlation with the change of the foot eversion.

Background: The quantitative analysis process on the data of COP revealed in the process of repetitive gait and running cycle is essentially required and through COP trajectories, the correlations between ground and feet can be effectively examined.

Method: Thirty young males participated in this study. They were asked to run on an instrumented treadmill (Bertec, USA) at speeds of 3.5m/s and 4.5m/s for running. A system of motion analysis cameras (Oqus 300, Qualisys, and Sweden) and pedar-X system (Novel GmbH, Germany) were used to collect joint angles and COP trajectories, and Shoelace Formula was used to calculate the area of multiple COP lines from running. The analysis variables were the area of COP, the COP range, the COP velocity, and the ankle joint eversion angle. The Pearson's correlation coefficient was calculated to investigate the relations between variables.

Results: The running at 4.5m/s showed the smaller area of COP and the range of COP, but the greater velocity of COP ($p<0.05$) in comparison with the running at 3.5m/s. There was a positive correlation between the area of COP and the anterior-posterior range of COP ($r=.350$). Additionally, there was a negative correlation between the area of COP and the maximum eversion angle of ankle joint ($r=-.418$).

Conclusion: The findings indicate that the method using the Shoelace Formula to calculate the area of COP was able to determine the difference between running speeds and predict the maximum eversion angle of the ankle joint.

Application: Based the results, the area of COP trajectories newly presented in this study is judged to be used as a variable to predict running speed and the eversion angle of the ankle joint.

Keywords: Shoelace formula, COP, Ankle eversion

1. Introduction

Running, one of the basic means to move the human body, is controlled through complex coordination of joints. Running can vary according to running speed, how to run, character, and habit, as well as physical characteristics (Shin et al., 2008; Tirosh and Sparrow, 2005; Whittle, 1990). Upon looking at the ankle joint motion during running, the inversion motion is shown before a foot touches the ground, and the eversion motion is shown from the moment a foot touches the ground until it is off the ground. The proper eversion motion is needed for a foot to touch the ground evenly, and it plays an important role of dispersing or diminishing impact delivered to human body upon landing (Cavanagh and Lafortune, 1980). However, the excessive eversion motion of the foot may cause an injury to the foot, ankle, lower leg, and knee (Clancy, 1982). The excessive eversion motion occurring during running, in particular, can be a cause of injury (Clement et al., 1984). A study of Ryu (2010) reports that the possibility of ankle joint injuries increases as the changes of ankle inversion and eversion become bigger.

The center of pressure (COP) is a point of action on the reaction force on the ground, with COP trajectories showing human body characteristics. Through COP trajectories, the correlations between ground and feet can be effectively examined (Chiu et al., 2013). The travel path of COP, revealed upon running, shows the correlation between the foot and ground, changing according to time and providing useful information including load change (Giacomozzi et al., 2002; Pataky et al., 2011). Cornwall and McPoil (2000) defined COP as the momentary point to which ground reaction force works and reported that COP location in the support section upon travel clearly moves in a direction from the heel to the toe. Alexander and Campbell (1990) and Fuller (1999) asserted that the projection of COP in the support section is gait line. Back and Iim (1997) and Park and Woo (2015) said COP has an important meaning for understanding human body movements because COP includes motions on the whole sole alongside load delivery. As such, COP showing the correlations and organic relations between the ground and foot is actively used for gait and running analyses (Diaz et al., 2018; Fischer and Wolf, 2016; Hansen et al., 2017; Louey et al., 2017; Lynall et al., 2017; Park and Woo, 2015; Peyer et al., 2017; Sugawara et al., 2016; Vlutters et al., 2017; Weaver et al., 2016; Weerasinghe et al., 2017; Zare and Maghooli, 2016; Zhai et al., 2017).

Despite high utilization of COP, previous studies have limitations for an objective analysis. Most previous studies calculated variability (Giacomozzi et al., 2002; Pataky et al., 2014), evaluate motions on the COP-shape moved from the heel to the toe in the stance phase of running (Kutílek et al., 2013), and analyze the angle of the joints where COP deviates from the foot array (Chiu et al., 2013). Using the method above, there are difficulties to examine the characteristics of COP data shown inside of the sole due to repetitive running in an integrated way, as running motions are evaluated with the mean value or deviation by analyzing one cycle of running. For the COP revealed in the process of gait and running, the need for interpretation of disorderly non-linear characteristics' complexity was raised due to overlapping characteristics in the limited space within the sole according to time (Carroll and Freedman, 1993; Harris et al., 1993; Newell et al., 1997).

It is reported that how far two close points can be apart as time elapses can be checked by applying Lyapunov exponent and that the study on the COP is useful for the evaluation of dynamic features and stability, but there is a limitation in quantification (Dingwell and Cusumano, 2010; Moraiti et al., 2007). As previous studies on COP were used as fragmental research such as local evaluation of the foot and qualitative shape comparison, there are limitations in clear evaluation and interpretation on the data of repetitive gait and running. Therefore, the quantitative analysis process on the data of COP revealed in the process of repetitive gait and running cycle is essentially required. An analysis on the correlations with repetitive movements of inversion and eversion motions of ankle joint, which is a direct cause of injury in the stance phase of running, is valuable in that it can widen the possibility of interpretation of COP data and can suggest a new analysis technique.

This study aimed to present the quantitative analysis method of COP data based on COP trajectories and to examine the correlations between maximum eversion angle and the ROM of inversion and eversion revealed in the stance phase of running. Therefore, this study presented how to calculate the COP data area anew, based on uninterrupted COP trajectories, calculated the range of COP and mean travel velocity, and examined the correlations between maximum eversion angle and the ROM of inversion and eversion in the running support section.

2. Method

2.1 Participants

This study selected 30 adult males in their 20s meeting shoe size US-9 and rear-foot striker (age: 21±2 yrs, height: 176.1±4.0cm, weight: 70.9±6.6kg) without lower limb disease history for the past six months and regularly doing exercise for more than an hour two times a week.

2.2 Materials and measurements

For this study, eight infrared cameras (Oqus 300, Qualysis, Sweden; 100Hz), a treadmill (Instrumented treadmill, Bertec, USA), and equipment to measure plantar pressure (Pedar-X in-shoe system, Novel GmbH, Germany; 100Hz) were used (Figure 1). The set experiment condition was running in two sets of speed (3.5m/s, 4.5m/s), and the experiment results were analyzed (Keller et al., 1996). The participants were instructed to wear the same shoes (FILA, Korea) to remove the shoe effect. As for the experiment procedure, eight infrared cameras were located around the treadmill, and 3D space coordinates were built. 14 reflection markers were attached to participant's right leg, the Pedar-X system was installed, and the participants did running at the two sets of speed. After they adapted to treadmill running for a minute, the 2-minute running data were collected.

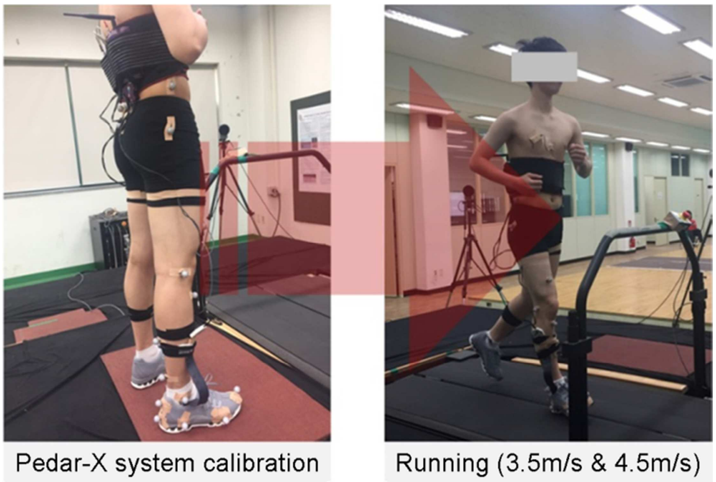

Figure 1. Experimental procedure

2.3 Data processing

From the running data from the two sets of speed, the data of 10 stances selected as performing continuously stable running were used for an analysis. Also, the medial and lateral and anterior and posterior ranges including COP area and mean velocity, and inversion and eversion angles of the ankle joints were calculated using the Matlab R0216a software (The Mathworks, USA).

To calculate the generated area through COP trajectories, this study used a formula Sholelace Formula, Braden (1986) calculating the vector data suggested by Braden (1986) (Figure 2). The formula calculating the inside area by connecting maximum exterior angle from the vector data existing in the phase system is as follows:

$$\text{Area} = \frac{1}{2}\left|\sum_{i=1}^{n-1} x_i y_{i+1} + x_n y_1 - \sum_{i=1}^{n-1} x_{i+1} y_i - x_1 y_n\right|$$

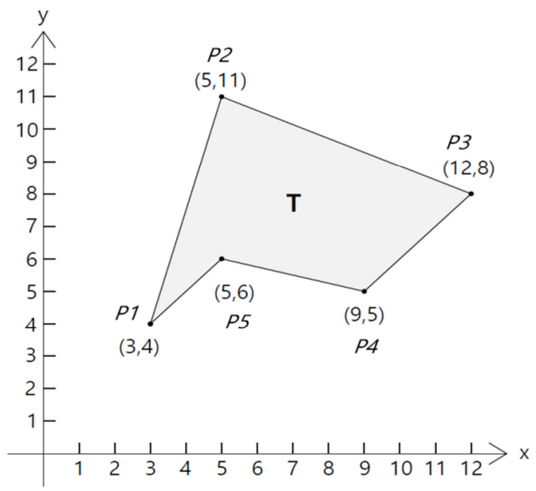

Figure 2. Visualization of the Shoelace Formula (Braden, 1986)

After calculating the following processing process through the collected COP coordinates in the Matlab (Matlab R0216a), the COP trajectories were quantified by participant, as COP area was analyzed with the repeated COP trajectories according to speed. In doing so, the area of the COP trajectories can be calculated from the second try points in Figure 3.b, where two lines are generated.

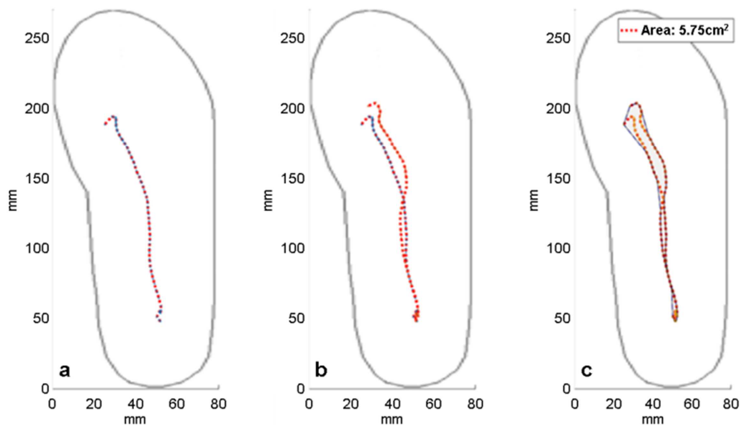

Figure 3. The process of creating the area from COP trajectories

Concerning 3D angle of the ankle joint as shown in Figure 4, the angle of the joint coordinate system (JCS) was calculated using the shank and rearfoot's segment coordinate system (SCS), based on Cardan's 3D angle calculation formula (Ryu and Hamill, 2003).

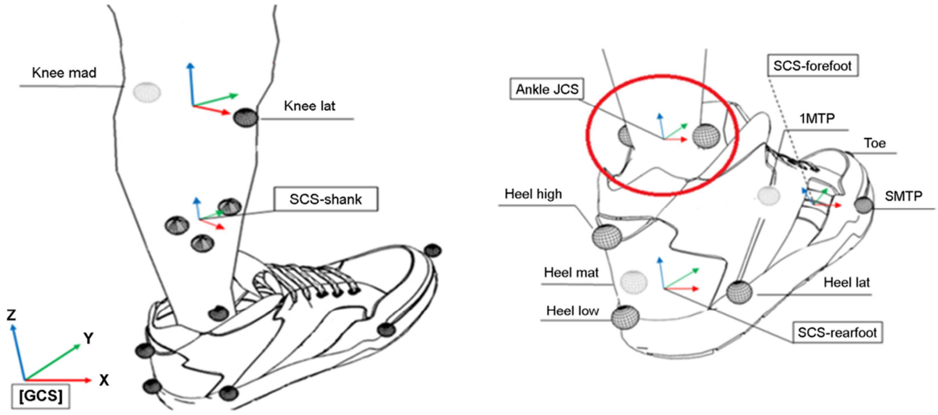

Figure 4. Joint coordinate system using marker set

2.4 Statistical analysis

SPSS 22 (IMB, USA) was used for statistical processing. This study conducted paired *t*-tests to examine differences between running speeds with regard to the area of COP trajectories, anterior and posterior and medial and lateral directional COP ranges, mean velocity, maximum eversion angle of the ankle joint, and ROM of inversion and eversion. To investigate correlations between variables, Pearson's correlation coefficient was used, and the correlation coefficient was examined between variables without classifying the running speed. The significance level was set as α = .05.

3. Results

This study presented the quantitative analysis method of COP, based on COP trajectories, and calculated the area of COP data, COP range and mean velocity, maximum eversion angle of the ankle joint, and ROM of inversion and eversion to examine correlations with the motions of the ankle joint revealed in the stance phase of running (Tables 1 and 2).

The area of COP data according to running speed was 13.61±3.30cm^2 at the speed of 3.5m/s, and 12.06±2.50cm^2 in the running speed of 4.5m/s (p=.013). The medial and lateral range of COP was 2.48±0.38cm at the speed of 3.5m/s, and 2.33±0.39cm at the speed of 4.5m/s. The anterior and posterior range of COP was 15.67±1.57cm at the speed of 3.5m/s and 14.84±1.84cm at the speed of 4.5m/s (p=.001). The medial and lateral velocity of COP was 10.71±1.54cm at the speed of 3.5m/s and 11.77±2.50cm at

Table 1. Descriptive information for COP variables during running of 3.5m/s & 4.5m/s

Variables	3.5m/s	4.5m/s	*p*
Area of COP (cm^2)	13.61±3.30	12.06±2.50	**0.013***
Medio-lateral (M/L) COP range (cm)	2.48±0.38	2.33±0.39	**0.001***
Antero-posterior (A/P) COP range (cm)	15.67±1.57	14.84±1.84	**0.001***
Medio-lateral (M/L) COP velocity (cm/s)	10.71±1.54	11.77±2.50	**0.003***
Antero-posterior (A/P) COP velocity (cm/s)	64.85±6.39	71.67±12.06	**0.001***

*Indicates statistically significant difference at α = .05.

the speed of 4.5m/s (p=.003). The anterior and posterior mean velocity of COP was 64.85±6.39cm/s at the speed of 3.5m/s and 71.67±12.06cm/s at the speed of 4.5m/s (p=.001), and significant differences were shown. Meanwhile, the maximum eversion angle of the ankle joint and the ROM of inversion and eversion did not show statistical differences according to running speed.

Table 2. Descriptive information for ankle joint angle during running of 3.5m/s & 4.5m/s

Variables	3.5m/s	4.5m/s	p
Maximum eversion angle (deg)	14.79±6.61	14.85±6.80	0.955
ROM of inversion & eversion (deg)	21.33±7.35	21.54±7.46	0.821

Table 3 and Figures 5 and 6 show the correlations between variables. The correlation coefficient between the area of COP and anterior and posterior range of COP was r=.350 (p=.006), and a positive correlation was revealed. However, the correlation between

Table 3. Pearson's correlation coefficient between ankle joint angle and COP variables

Variables	M/L COP range (cm)	A/P COP range (cm)	M/L COP velocity (cm/s)	A/P COP velocity (cm/s)
Area of COP (cm^2)	r=-.052 (p=.692)	**r=.350 (p=.006)***	r=-.219 (p=.093)	r=.012 (p=.928)
Maximum eversion angle (deg)	r=.124 (p=.347)	r=-.094 (p=.476)	r=.165 (p=.207)	r=-.065 (p=.623)
ROM of inversion & eversion (deg)	r=-.104 (p=.429)	r=.065 (p=.624)	r=-.104 (p=.429)	r=-.085 (p=.520)

*Indicates statistically significant difference at α = .05.

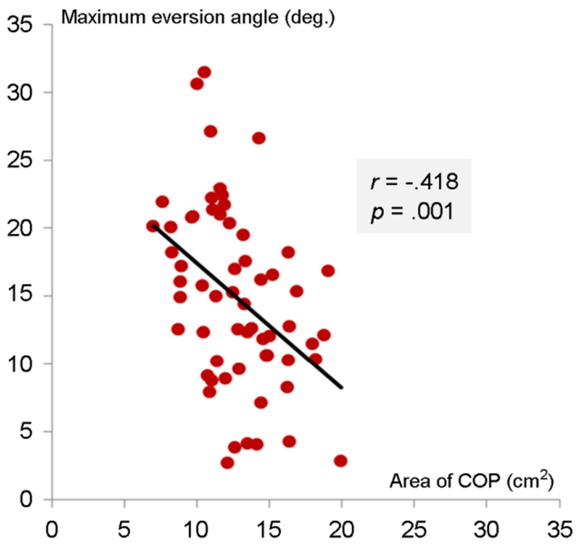

Figure 5. Correlation coefficient between the area of COP and maximum eversion angle

the inversion and eversion angles of the ankle joint and COP variables did not show a statistically significant correlation. Upon looking at the correlation between the area of COP and maximum eversion angle of the ankle joint, the correlation coefficient was r=-.418 (p=.001), and a negative correlation was shown. However, the correlation between the area of COP and the ROM of inversion and eversion of the ankle joint did not show a statistically significant correlation.

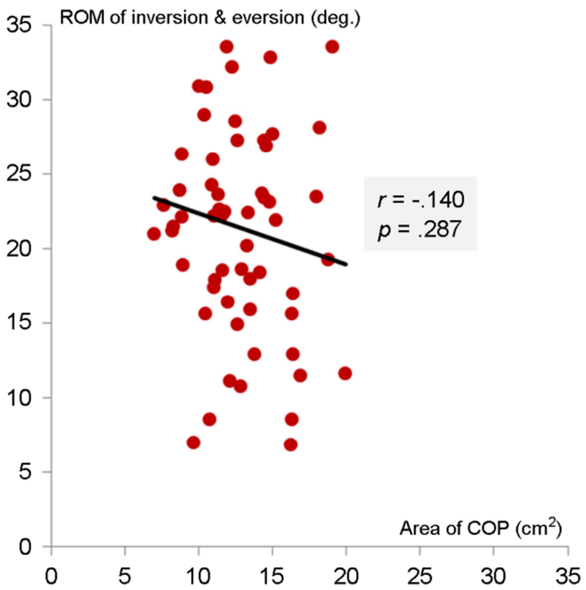

Figure 6. Correlation coefficient between the area of COP and ROM of inversion & eversion

4. Discussion

This study aimed to present a quantitative analysis of repetitive COP data based on the accumulated COP trajectories and to examine correlations between the maximum eversion angle of the ankle joint and the ROM of inversion and eversion. To this end, this study analyzed COP data area, mean COP velocity, maximum eversion angle of the ankle joint, and ROM of inversion and eversion in the stance phase of running at the two sets of speed, and calculated the correlation coefficient between variables.

First, the COP range and mean velocity, as well as COP area, showed statistically significant differences depending on running speed. As running speed increased, the COP range was smaller, and the COP area also decreased; however, mean COP velocity increased. In relation to the studies reporting that the medial and lateral movements of human body center decrease and the anterior and posterior movements increase as gait speed increases (Orendurff et al., 2004; Tesio et al., 2010; Jansen et al., 2014), the foot's touching area appears to decrease according to increase in running speed as for the area and the COP range, but COP velocity representing human body movements is judged to increase (Chung et al., 2001). In relation to previous studies asserting that there are difficulties to quantitatively evaluate cumulative characteristics of movements within the sole (Carroll and Freedman, 1993; Dingwell and Cusumano, 2010; Harris et al., 1993; Moraiti et al., 2007; Newell et al., 1997), the method of COP area calculation shown in this study may suggest a new approach on the analysis of the change of COP movement.

Second, the maximum eversion angle and the ROM of inversion and eversion showed an increasing trend as running speed increased, but there was no statistical difference. Like a previous study (Cavanagh and Lafortune, 1980) reporting that the eversion movements of the ankle joint are revealed due to the role of dispersing and decreasing impact delivered to human body in the landing section of running, the reason the maximum eversion angle and the ROM of inversion and eversion slightly increased is considered to be related with the mitigation of impact generated in the landing phase.

Third, no high correlation between the area of COP and ROM of inversion and eversion of the ankle joint was shown. As for the correlation between the area of COP and maximum eversion angle of the ankle joint, the correlation coefficient was r=-.418, and a negative correlation was revealed. Regarding the correlation between the area of COP and the anterior and posterior range of COP, the correlation coefficient was r=.350, and a positive correlation was revealed. This can be interpreted that the maximum eversion angle of the ankle joint increases, as the area of COP is smaller.

The factor affecting the area of COP can be the anterior and posterior range of COP, rather than the medial-lateral range of COP. The reason why the area of COP decreased as running speed increased is judged as the result of the reduction of the anterior and posterior range of COP. Maximum impact force on the foot touching the ground is 2~3 times more than one's weight upon running. It is reported that absorbing impact into body movements occurs in the naturally performing process of the eversion motion of the ankle joint and curvature motion of the knee joint at the moment of landing (Clement et al., 1984) especially as excessive eversion exercise in the stance phase of running is reported to cause lower limb joint's injury and wound (Clancy, 1982; Clement et al., 1984; Ryu, 2010), the area of COP is conjectured to be used as a variable to predict the eversion angle of the ankle joint.

5. Conclusion

This study aimed to propose a new method to calculate area for repetitive COP trajectories and to examine correlations between maxim eversion angle and the ROM of inversion and eversion revealed in the stance phase of running. 30 healthy adult males in their 20s wearing the same shoes performed running at the two sets of speed. This study analyzed the area of COP, COP range, mean velocity, maximum eversion angle of the ankle joint, and ROM of ankle joint's inversion and eversion, and examined relations by calculating the correlation coefficient between variables. The conclusion is as follows: First, the COP area and COP range were smaller at the speed of 4.5m/s than at the speed of 3.5m/s (p<.05). Second, the mean velocity of COP was higher at the speed of 4.5m/s than at the speed of 3.5m/s (p<.05). Third, a positive correlation coefficient between the COP area and anterior and posterior range of COP was shown (r=.350, p<.05). Fourth, a negative correlation coefficient between the COP area and maximum eversion angle of the ankle joint was shown (r=-.418, p<.05). Putting together the above results, the COP range and COP area decreased as running speed increased, but the COP velocity increased. The COP area showed a positive correlation with the anterior and posterior range of COP, and the maximum eversion angle of the ankle joint increased as the COP area decreased. Finally, the area of COP trajectories newly presented in this study is judged to be used as a variable to predict running speed and the eversion angle of the ankle joint.

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