KJSB

Korean Journal of Sport Biomechanics 2017; 27(2): 133-140
http://dx.doi.org/10.5103/KJSB.2017.27.2.133
http://e-kjsb.org eISSN 2093-9752

ORIGINAL

Relationship between Center of Pressure and Local Stability of the Lower Joints during Walking in the Elderly Women

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Received : 27 April 2017
Revised : 07 June 2017
Accepted : 08 June 2017

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Objective: The purpose of this study was to determine the relationship between center of pressure (CoP) and local stability of the lower joints, which was calculated based on approximate entropy (ApEn) during walking in elderly women.

Method: Eighteen elderly women were recruited (age: 66.4±1.2 yrs; mass: 55.4±8.3 kg; height: 1.56±0.04 m) for this study. Before collecting data, reflective marker triads composed of 3 non-collinear spheres were attached to the lateral surface of the thigh and shank near the mid-segment to measure motion of the thigh and shank segments. To measure foot motion, reflective markers were placed on the shoe at the heel, head of the fifth metatarsal, and lateral malleolus, and were also placed on the right anterior-superior iliac spine, left anterior-superior iliac spine, and sacrum to observe pelvic motion. During treadmill walking, kinematic data were recorded using 6 infrared cameras (Oqus 300, Qualisys, Sweden) with a 100 Hz sampling frequency and kinetic data were collected from a treadmill (Instrumented Treadmill, Bertec, USA) for 20 strides. From kinematic data, 3D angles of the lower extremity's joint were calculated using Cardan technique and then ApEn were computed for their angles to evaluate local stability. Range of CoP was determined from the kinetic data. Pearson product-moment and Spearman rank correlation coefficient were applied to find relationship between CoP and ApEn. The level of significance was determined at $p<.05$.

Results: There was a negative linear correlation between CoP and ApEn of hip joint adduction-abduction motion ($p<.05$), but ApEn of other joint motion did not affect the CoP.

Conclusion: It was conjectured that ApEn, local stability index, for adduction/abduction of the hip joint during walking could be useful as a fall predictor.

Keywords: Fall, CoP, ApEn, Walking, Stability

INTRODUCTION

Falls represent a serious health threat for the elderly. More than one-third of all elderly residents in Korea, aged 65 years or older, experience at least one fall each year. A quarter of those who experience such a fall are hospitalized. Moreover, it has been reported that among all accident cases involving the elderly, half of such cases involve falls (Health, 2017).

As the elderly age, they experience decreased muscle contraction capacity due to gradual reduction in muscle fibers, and as a result, their range of motion also becomes reduced (Fontera, Meredith, & O'Relly, 1989), which may cause balance and gait disturbances that make these elderly vulnerable to falls (Rubenstein & Josephson, 2002). Decline in balance regulation mechanism due to aging can cause falls, which may ultimately lead to serious injuries (Mahoney, 1998). Lack of balancing ability among the elderly magnifies the risk of falls (Gauchard, Gangloff, Jeanel, & Perrin, 2003; Rao, 2005), and thus, it is not an exaggeration to say that falls among the elderly depend on maintaining their balancing ability (Johnell & Kanis, 2006). Because such balancing ability has an impact on falls, it is also used as a predictor of fall incidences (Guralnik, Ferrucci, Simonsick, Salive, & Wallace, 1995). Balance refers to the ability to maintain the center of gravity on a plane of support. In other words, it refers to the process of continuing to maintain postural stability that allows a person to control his or her center of mass relative to a supporting base, which has an important influence on the ability to perform various movements, such as maintaining stability while standing upright, controlling weight bearing, and walking (Cohen, Blatchly, & Gomblash, 1993; Geurts, Ribbers, & Knoop, 1996).

The ability to maintain physical balance can be quantified by measuring stability. One of the methods for quantifying fall-related physical stability involves observing the center of pressure (CoP). Because CoP is defined as the point where the sum of normal force that acts on a plane of support is exerted by the body, it is being used as a determinant for postural stability. Consequently, it is also being used as a

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determinant for falls in the elderly (Teasdale & Simoneau, 2001). Ferine, Gryfe, Holiday, & Liewellyn (1982) compared CoP between elderly with no falls experience and elderly with at least one fall in a year and claimed that elderly with falls experience had significantly larger mean CoP sway velocity. Collins & de Luca (1995) used CoP range to analyze postural sway in quiet upright standing elderly and reported that elderly with larger sway range had higher potential falls risk. Maki, Holliday, & Topper (1994) claimed that the size of medial-lateral (ML) sway of CoP under eyes closed condition served as a somewhat accurate predictor of future falls even for elderly with no falls experience. Melzer, Kurz, & Oddsson (2010) reported that an investigation on 99 elderly subjects (65~91 years of age) showed that the mean ML CoP range and area under standing upright with eyes closed condition were higher among those with falls experience than those without. Moreover, Stel, Smit, Pluijm, & Lips (2003) measured CoP under the condition of using a moving force plate with restricted field of vision and pointed out physical ML sway as an independent predictor of falls. In addition, other researchers have also conducted studies on determining and predicting falls by calculating the CoP with the use of a force plate (Bergland, Jarnlo, & Laake, 2003; Melzer & Oddsson, 2004; Piirtola & Era, 2006). As shown, many researchers determined postural stability through CoP sway range and suggested it as a potential falls-related predictor.

Another method of determining postural stability involves using variability. Variability refers to a method of quantifying the size of variations among certain data, with relatively larger size being considered to represent greater instability. Such variation is an indicator of instability, and thus, it is also used as a predictor for falls in the elderly (Verghese, Holtzer, Lipton, & Wang, 2009). Gait variability represents quantification of the size of stride variations during walking. Many researchers have insisted that increased variability in general gait parameters is sufficient to predict falls in the elderly (Hausdorff, Rios, & Edelberg, 2001; Verghese et al., 2009; Hahn & Chou, 2003). Paterson, Hill, & Lythgo (2011) claimed that increased variability has the potential to have an effect from misstep to falls in the elderly. Recently, a study on young and elderly women by Ryu (2017) identified gait characteristics of elderly women through approximate entropy (ApEn) analysis, a time series analysis method, on the periodic variation, meaning variability, in flexion/extension movement of lower extremity joints and estimated potential falls due to aging.

As shown, stability indicators, such as CoP and variability, have often been analyzed to predict falls in the elderly. Up to now, analysis of CoP during walking used linear techniques to derive the results from just few strides selected for determining the variable of systemic stability, whereas using time series method for variability analysis has been used to determine the variable of local stability by observing many cycles of movements in specific body parts (Ryu, 2014). Although the analysis methods for these two variables in studies on falls in elderly have been different, their roles as predictors for determining the probability of actual and potential falls through stability may be the same. Despite these 2 variables being used as indicators of stability for determining falls, there are almost no studies that have conducted in-depth investigation on the relationship between these two variables. Investigating the level of relationship between local and systemic stability indicators in the joints of the elderly who face decreased stability due to weakened lower extremity joint functions as a result of aging can be viewed as meaningful work for expanding the horizon in study methodologies for predicting falls. Moreover, studies on local stability with respect to kinematics of lower extremity joints during walking may be needed to determine whether it can also be used as an indicator of falls in the elderly. In other words, there is a need for studies that can investigate whether kinematic variations in the lower extremity joints during walking can predict falls in the elderly, and if so, movements in which joint(s) may be useful for determining and predicting falls.

Accordingly, the objective of the present study was to investigate the relationship between variability in 3-dimensional (3D) movement of lower extremity joints and CoP sway range during walking in elderly women who have a relatively higher fall rate than males. For this objective, the following details were considered particular points of interest: 1) Observation of anterior-posterior (AP) and ML CoP range of twenty strides during walking in the elderly; 2) calculating 3D angular displacement in the lower extremity joints during twenty strides for calculation of ApEn for determining their local stability; and 3) examination of the correlation between CoP and ApEn.

METHODS

1. Participants

The participants in the present study consisted of eighteen elderly women (mean age: 66.4±1.2 yrs, mean weight: 55.4±8.3 kg, mean height: 1.56±0.04 m, and mean preferred walking speed: 0.77±0.11 m/s) (Ryu, 2017).

2. Measurements

Kinematic and kinetic data were collected while the elderly women walked on a treadmill at their preferred speed. For collection of kinematic data of the lower extremity joints during walking, a set of three triangular markers that formed non-collinear lines was set in the center of femoral segment and lower legs. On the foot segment, markers were attached on the heel, lateral side of the ankle, and fifth metatarsal head. On the hip, markers were attached on the right anterior superior iliac spine, left anterior superior iliac spine, and sacrum. As the participants walked at their normal walking speed (mean 0.77±0.11 m/s), six high-speed digital infrared cameras (Oqus 300, Qualisys, Switzerland) set up near the treadmill were used to collect 3D coordinates of these markers with a sampling rate of 100 Hz. The spatial settings for acquiring the coordinates were established via non-linear transformation (NLT) method by placing an L-frame rigid body with four markers of known size behind a corner of the treadmill. Axes for the coordinates were set as a room coordinate system with +Z representing vertically upward direction relative to the corners of the L-frame; +Y representing the direction of movement; and +X representing the direction where +Y crossed +Z. The coordinate axes settings for the markers attached to the body used the same directions as the room coordinate system. In order to obtain anatomical data that will serve as the bases for calculating 3D angles of the lower extremity joints, the coordinates of the

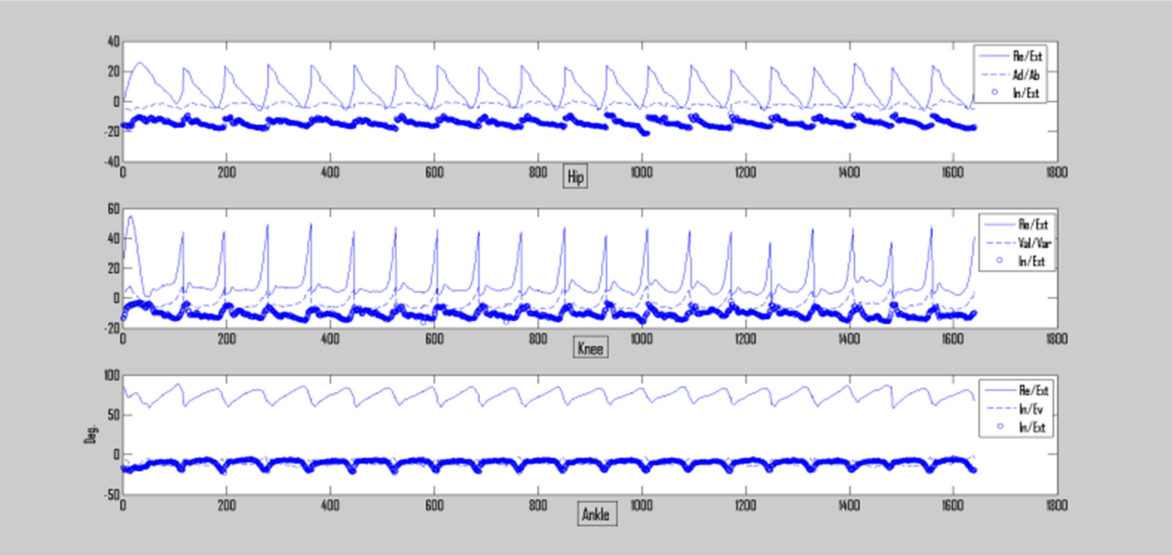

Figure 1. Example of 3-dimensional hip, knee, and ankle for an individual.

markers were acquired in upright position for about three seconds with a pre-calibrated camera, prior to actual walking. Kinetic data were obtained via a force plate installed on the treadmill by taking the moment and force in three directions at a sampling rate of 1,000 Hz and synchronizing with kinematic data. Data collection took place over at least 20 strides, without the participant being aware, and the participants were given enough warm up time to become familiar with treadmill walking prior to actual data collection.

3. Data processing and Statistical analysis

Collected data were used to calculate 3D angles of the lower extremity joints and their ApEn and CoP. The calculation of 3D angles in the lower extremity joints used the Cardan XYZ sequence method (Hamill & Ryu, 2004), calculating values for 20 strides in the right foot support phase. The support phase was established as the range from the moment of the right foot touching down on the treadmill when the vertical ground reaction force (GRF) is ≥5 N to the moment of lifting off when GRF is <5 N. To examine local stability of 3D angles of hip, knee, and ankle joints calculated in this manner, a nonlinear method of ApEn was used to calculate the periodicity (Ryu, 2016), with larger ApEn values being considered to show greater instability (Preatoni et al., 2014; Ryu, 2016). For CoP calculation, 6 components of GRF data (Fx, Fy, Fz, Mx, My, and Mz) obtained from the treadmill were used on the right foot support phase for 20 strides, just as in the calculation of kinematic variables. Prior to CoP calculation, a fourth order Butterworth filter was used to eliminate noise from the aforementioned data. Here, the cut-off frequency used was the frequency at the point when the cumulative power spectral density (PSD) reached 99.9% (Stergiou, Giakas, Byrne, & Pomeroy, 2002). Using the data that were processed in this manner, LM CoP (CoPx) and AP CoP (CoPy) were calculated using the formula My/Fz and Mx/Fz, respectively. CoP was quantified as the absolute value of the difference between the maximum and minimum values, with the mean value of 20 strides being used. CoP values calculated in the present study were assumed to be parametric, whereas ApEn values were considered to be nonparametric since normality could not be assumed (Ryu, 2017). Therefore, in order to investigate the degree of correlation between the local stability indicators of 3D angles of the lower extremity joints ApEn and CoP, the present study used both Pearson's product-moment correlation coefficient (PPMCC), a parametric correlation analysis method, and Spearman rank correlation coefficient (SRCC), a nonparametric correlation analysis method. Degree of correlation was determined to be statistically significant when the results from these two analysis methods simultaneously satisfied the significance level. The threshold for the significance level was set to 5%.

RESULTS

Figure 1 shows the results of 3D angles of hip, knee, and ankle joints for 20 strides, as derived by the methods mentioned above. Figure 2

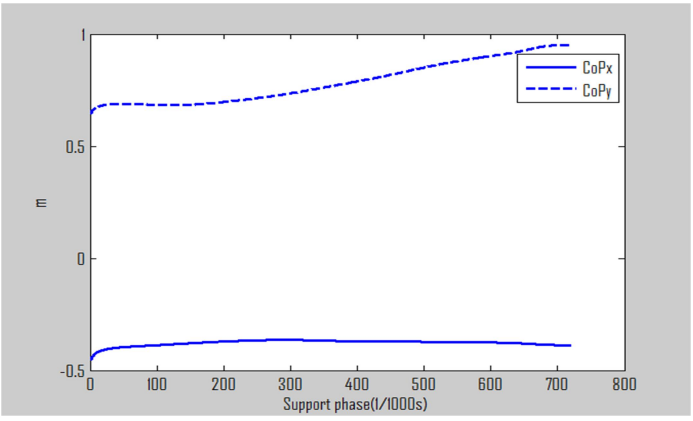

Figure 2. Example of an individual's center of pressure (CoP).

shows CoP in the support phase. Correlations between ApEn and CoP for 3D angular movement of lower extremity joints were as shown in Table 1 and Figure 3~5.

According to these results, CoPx and ApEn value for local stability of adduction/abduction angular movement of the hip joint showed PPMCC of r=-.54 (p=.02) in the parametric correlation and SRCC of r=-.68 (p=.001) in the non-parametric correlation analysis. Therefore, both analyses simultaneously showed statistically significant negative linear correlation. Moreover, CoPx values and ApEn values for flexion/extension and internal/external rotation angles of the hip joint showed very low correlations in both parametric and non-parametric correlation analyses. Furthermore, CoPy values and ApEn values of angular movement in three directions of the hip joint showed low negative correlations, which were not statistically significant in both parametric and non-parametric correlation analyses.

CoPx and ApEn values for flexion/extension, adduction/abduction, and internal/external rotation of the knee joint did not show statistically significant results in both parametric and non-parametric correlation analyses. CoPy and stability of angular movement in three directions in the knee joint also did not show statistically significant correlations in both parametric and non-parametric correlation analyses.

CoPx and ApEn values for flexion/extension of the ankle joint showed

Table 1. Parametric and non-parametric correlation coefficients and p-values between approximate entropy (ApEn) and center of pressure (CoP) range

Joint	Direction	CoPx		CoPy	
		Parametric	Non-parametric	Parametric	Non-parametric
Hip (ApEn)	Flex/ext	-.10 (.69)	-.22 (.36)	-.28 (.25)	-.34 (.16)
	Add/abd	-.54 (.02)*	-.68 (.00)*	-.21 (.38)	-.33 (.17)
	In/ext Rot	-.11 (.65)	-.05 (.81)	-.13 (.58)	-.15 (.53)
Knee (ApEn)	Flex/ext	.04 (.85)	0.23 (.34)	.13 (.60)	.13 (.59)
	Add/abd	.12 (.63)	0.14 (.57)	-.16 (.50)	-.22 (0.37)
	In/ext Rot	-.36 (.13)	-0.25 (.31)	.11 (.66)	.04 (0.87)
Ankle (ApEn)	Flex/ext	-.52 (.02)*	-0.44 (.06)	-.12 (.61)	-.12 (0.60)
	Add/abd	-.26 (.27)	-0.16 (.52)	-.26 (.29)	-.36 (0.13)
	In/ext Rot	-.28 (.25)	-0.41 (.08)	-.17 (.48)	-.26 (0.29)

*: p<.05

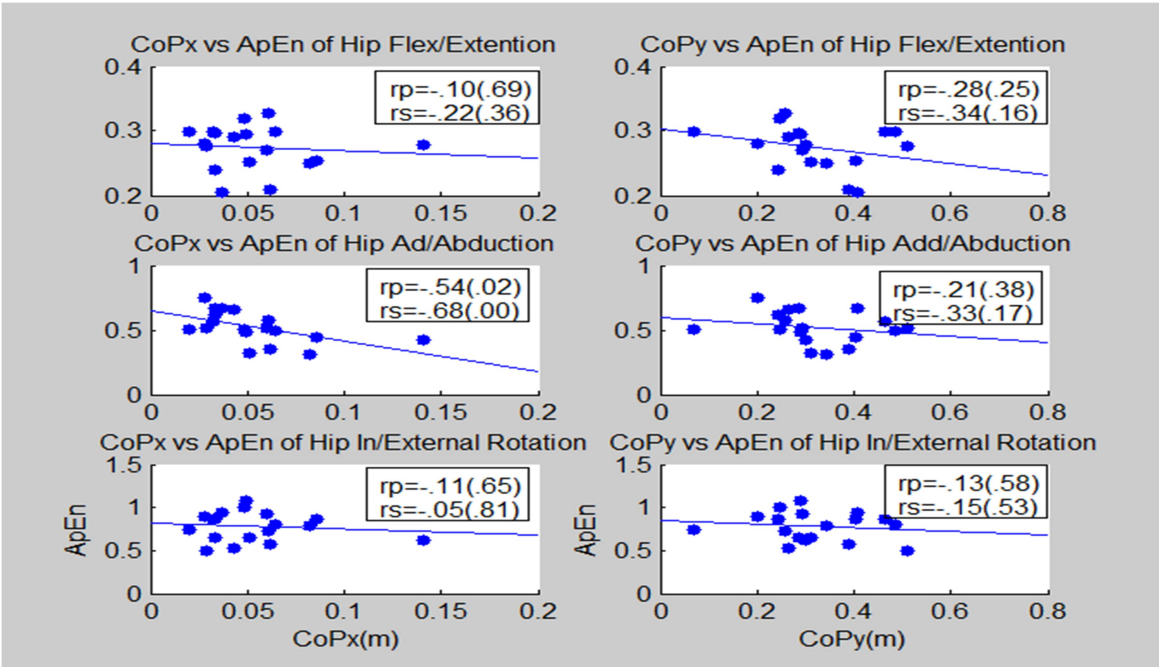

Figure 3. Scatterplot and correlation coefficients between approximate entropy (ApEn) of 3-dimentional hip joint angles and center of pressure (CoP). rp and rs indicate Pearson and Spearman correlation coefficient, respectively.

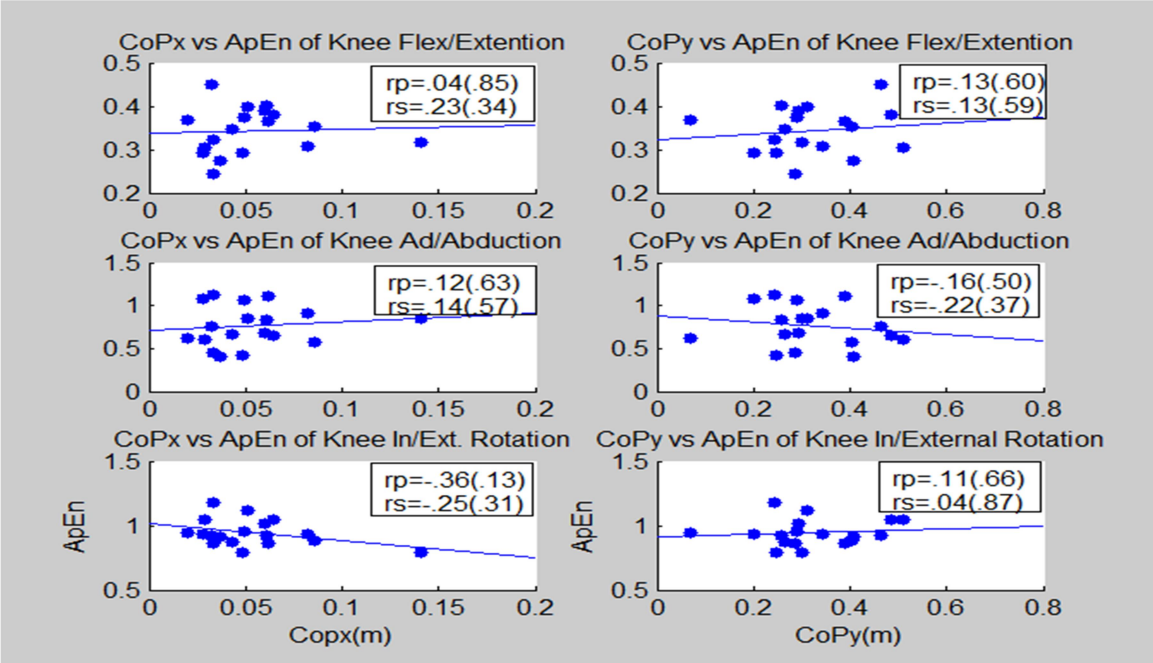

Figure 4. Scatterplot and correlation coefficients between approximate entropy (ApEn) of 3-dimensional knee joint angles and center of pressure (CoP). rp and rs indicate Pearson and Spearman correlation coefficient, respectively.

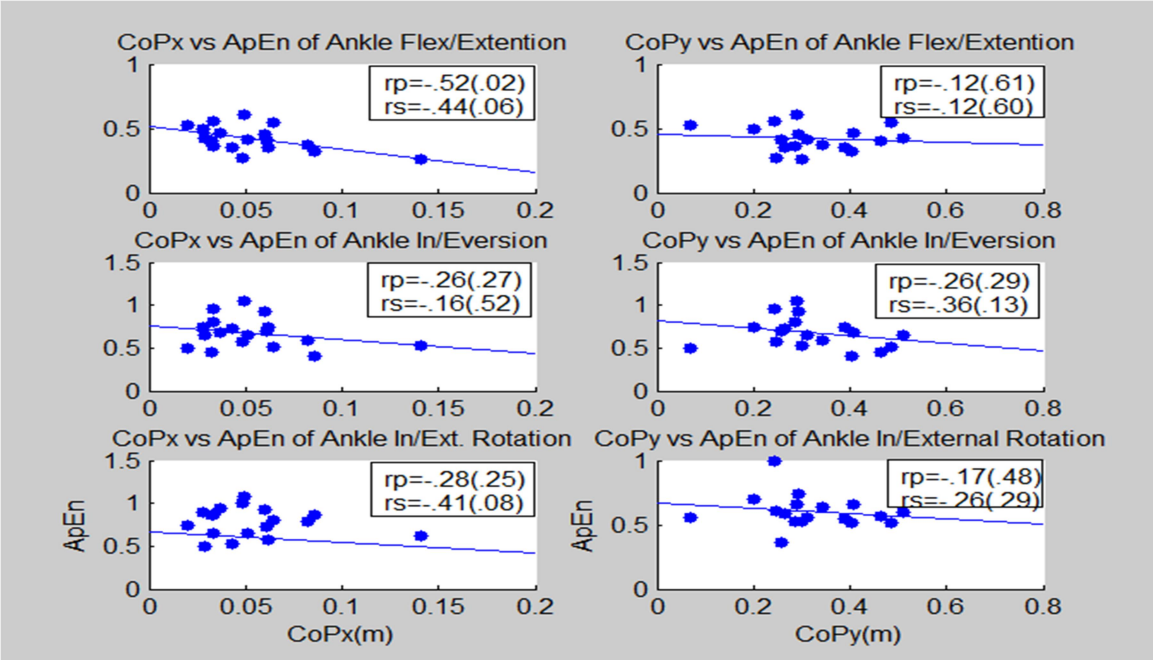

Figure 5. Scatterplot and correlation coefficients between approximate entropy (ApEn) of 3-dimensional ankle joint angles and center of pressure (CoP). rp and rs indicate Pearson and Spearman correlation coefficient, respectively.

a clearly negative linear correlation with PPMCC of r=-.52 (p=.02) in the parametric correlation, but showed SRCC of r=-.44 (p=.06) in the non-parametric correlation analysis, which was not statistically significant. Moreover, CoPx and ApEn values for adduction/abduction and internal/external rotation angles of the ankle joint did not show statistically significant correlations in both parametric and non-parametric correlation analyses. Furthermore, CoPy and ApEn values of angular movement in 3 directions of the ankle joint showed overall low negative correlations, which were not statistically significant in both parametric and non-parametric correlation analyses.

DISCUSSION

As the elderly age, they experience decreased muscle contraction capacity due to gradual reduction in muscle fibers, and as a result, their range of motion also becomes limited (Frontera, Meredith, O'Relly, Knuttgen, & Evans, 1988). Muscle atrophy, decreased muscle strength, and reduced muscle function have a negative effect on maintaining balance (Schlicht, Camaione, & Owenet, 2001). In particular, decreased muscle strength in the lower extremities has a major impact on balance and is known as a major cause of falls (Ferine, Gryfe, Holiday, & Liewellyn, 1982). Studies that determined stability by examining balance based on such theoretical background have focused mostly on falls in the elderly. Up to now, CoP has been used as a major indicator of stability for predicting falls (Collins & De Luca, 1993; Owings, Pavol, Foley, & Grabiner, 2000; Piirtola & Era, 2006). Among other indicators of stability for predicting falls in the elderly, one that has received recent attention is the local stability that is determined in non-linear analysis by observing periodicity, meaning variability, with the use of time series data (Ryu, 2017). As mentioned above, CoP uses a discrete method that analyzes some portions of steps or strides, assuming that they had the same periodicity. However, a time series analysis is a continuous analysis method that observes data over a set period of time (Verghese et al., 2009). Although the process of deriving the two variables is different, their utilization goal of determining stability is the same.

The present study aimed to investigate the degree of correlation between CoP range and local stability in 3D movements of the lower extremity joints derived through ApEn, one of the time series analysis methods, during walking in the elderly. Analysis of the correlation between local stability in 3D movements of the lower extremity joints and ML and AP CoP ranges showed that the correlation between local stability and CoP ranges of the knee and ankle joints was low, whereas in the hip joint that is closer to the center of mass, adduction/abduction movement and CoPx showed a negative linear correlation that was statistically significant. In other words, local stability of adduction/abduction in the hip joint was low but CoPx range was high. Variability during walking is an indicator of instability, and as such, it is considered a predictor of potential falls in the elderly. Increased variability among gait parameters was claimed to be a predictor of falls in the elderly by some studies (Hausdorff et al., 2001; Verghese et al., 2009; Maki, 1997). Moreover, within the CoP sway range, the magnitude of ML CoP range has been identified by precedent studies as a predictor of falls in the elderly that indicates the state of instability. Maki et al. (1994) and Bergland et al. (2003) claimed that the magnitude of ML CoP range is a somewhat accurate predictor of future falls even in elderly with no recent fall experience, while Melzer & Oddsson (2004) reported that ML sway parameter was a variable that can differentiate elderly who have experienced two or more falls in the past 6 months. Stel et al. (2003) measured CoP and pointed out that ML sway range of the body is an independent predictor of falls, while Melzer et al. (2010) reported that ML CoP range and area were clear indicators for differentiating between fallers and non-fallers. As shown, many studies have reported the magnitude of ML CoP range as a predictor of falls. These precedent studies determined the potential for falls by interpreting large ML CoP range and ApEn values, variability indicator, to mean greater instability. Therefore, these two factors maintaining a proportional linear correlation can be viewed as being consistent with the claims made in precedent studies that analyzed these two factors. However, in the present study, statistically significant correlation was found only between local stability of adduction/abduction movement in the hip joint and CoPx, which was an inversely proportional linear correlation. It is determined that the reason for this is because the local stability of adduction/abduction movement in the hip joint had a complex effect on the absolute value of CoPx that is derived from an inversely proportional relationship with the normal force and proportional relationship with AP axial moment. An assumption that can be taken into account based on the calculation of CoP range is that high periodicity of adduction/abduction movement in the hip joint during walking, meaning stability, did not affect AP axial moment, but only affected normal force to cause changes in CoP sway value. In other words, it is assumed that under unstable state, meaning low periodicity of adduction/abduction movement in the hip joint, the value of normal force become large, which induced the absolute value of CoPx to become small. Another assumption to take into consideration is that the stability of adduction/abduction movement in the hip joint during walking did not affect normal force, but affected AP moment to cause changes to CoPx. In such a case, local stability of the hip joint has a major impact on AP axial moment to induce the absolute value of CoPx to increase. The final assumption is that the difference in the stability of movement in the hip joint affected both normal force and AP axial moment at the same time to have an impact on CoPx. Proving such assumptions is believed to be another focus in future in-depth studies but it is believed that these assumptions serve the purpose of explaining the negative correlation between CoPx and local stability of adduction/abduction movement in the hip joint during walking. The results in the present study showed local stability of adduction/abduction movement in the hip joint, which had a clearly negative linear correlation between CoPx, and it is believed that this can be used as a predictor of falls in the elderly.

The results in the present study were inconsistent with the theoretical interpretation that larger variability in movement generally means greater instability. However, the results were consistent with the study by Chiu & Chou (2012, 2013), which reported that decreased variability in the pattern of coordination between joints during walking appears with aging and it increases the risk of falls. In order to determine the relationship between variability and stability during exercise, additional studies that take into account various situations, such as variability variables, joints and segments, and age are needed.

Therefore, additional studies with comparative analysis of local stability with consideration of differences in abductor/adductor muscle strength in the hip joints in elderly with and without fall experience are need to secure greater level of reliability for the findings of the present study.

CONCLUSION

Based on the investigation of the correlation between local stability of lower extremity joints derived from ApEn and ML CoP range in

elderly women during walking, the following conclusions were derived. When the local stability of adduction/abduction movement in the hip joint is low during walking, ML CoP range appears higher. In other words, a clearly negative linear correlation was found between ML CoP range and local stability of adduction/abduction movement in the hip joint. Therefore, it is concluded that ApEn, which is an indicator of local stability in adduction/abduction movement in the hip joint, among lower extremities joints, has a potential for the use as a predictor of falls during walking.

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