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Research Article
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A Comparison between Static and Dynamic Stability in Postural Sway and Fall Risks

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Abstract

The purpose of this study is to investigate the static stability of postural sway and compare it with dynamic stability by practical experiments. It can help the selection of appropriate personnel for highly exposed tasks and reduce fall risks and injuries. For static stability, index of COG% is defined regarding anthropometric specifications including height, BOS width and length and sway angles. Therefore, tabular guidelines can be developed so that balance status for each operator can be anticipated. In terms of dynamic stability, maximum Lyapanov exponents are calculated for time series data collected from gait analyzer tests and a written code in Matlab. The results reveal acceptable correlation between index of static and dynamic stability and hence can provide useful information for ergonomic concerns.

Keywords: Postural sway; Static stability; Dynamic stability; Balance

Introduction

Stability is one of the important factors in preventing falls while doing daily activities [1,2]. It has been the subject of many studies both in standing upright or sway postures [3,4]. It has also been studied for different groups of people in terms of age, gender and occupations [5-8]. For building construction operators who work on high structures, the balance becomes more critical because it may lead to severe injuries or even death [9,10].

Epidemiologic evidence indicates that injuries related to loss of stability and falls are prevalent in many countries [11]. In the United States, up to 20% of all compensable industrial accidents reportedly result from falls [12]. In the construction industry that workers must stand or walk on high narrow structures, fall is considered as the main cause of mortality and the second reason of nonfatal injuries [12]. According to the ILO, in construction industry, at least 60,000 fatal accidents occur annually that its major cause is fall from height due to loss of balance [13]. The main reason in 17% of occupational accidents per year recorded by Swedish information system is related to falls [14].

Both physiological and neurological factors affect stability [15,16]. In this study, physiological factors and their relation to anthropometric factors of human is investigated through a practical experiment on the participants. In previous studies, two types of stability, static and dynamic, have been investigated separately and the corresponding indices have been used [17-20]. In this study, both are considered in relation to each other in postural sway.

Postural sway is one of the most routine positions of the body either in industrial tasks like assembling different parts or in non-industrial tasks like balance exercises [1]. It can be described through the main rule of static stability: keeping the COG within the base of support boundaries. Most of the studies in static stability follow this rule [5,21,22]. For example Holbein et al. used the index COG% to access the static postural stability [23].

Computational modelling is used for testing postural stability [24-26]. However, most of the balance machines use dynamic stability indices. One of the well-known dynamic stability indices is maximum Lyapunov exponent introduced by Aleksandr Lyapunov in 1892 [27]. This is an index for local stability and its magnitude shows the divergence rate of two points in state space which were closed to each other at the beginning [28].

In this paper, static stability is studied in relation to anthropometric range for COG, BOS and other parameters. For dynamic stability, a Matlab code is written and run in order to calculate Lyapunov exponent. Finally, the results of the two indices are compared and discussed in detail.

Static Stability

Methods

In this research, COG% (Center of gravity %) is used as the index of static stability. It shows the percentage of the base of support covered by the body's center of gravity projection on the horizontal plane [23]. So higher COG% means the person can better control his/her stability and sway angle can rise. Figure 1 and Equation 1 illustrate how COG% is calculated in anterior sway.

$$\text{COG}\%=x/(W\_BOS/2) \qquad (1)$$

Where W_{BOS} width of the BOS is, W_{BOS} is length of the BOS and is the distance between COG Projection in vertically erect position (point 1) and swayed position (point 2) in Figure 1. Hence this index is directly correlated with the BOS dimensions.

Using the above method, we can develop a range of parameters and determine the state of balance for each setting in order to reach two main objectives: 1) The upper limit for COG% in work positions with high risk like working on pylons or Scaffolds is determined (where the selection of a person with appropriate anthropometric characteristics is desired); 2) A comparison between the calculated COG% of a person with specific anthropometric characteristics and its limits in specific work condition is done (where the risk of the task is determined and

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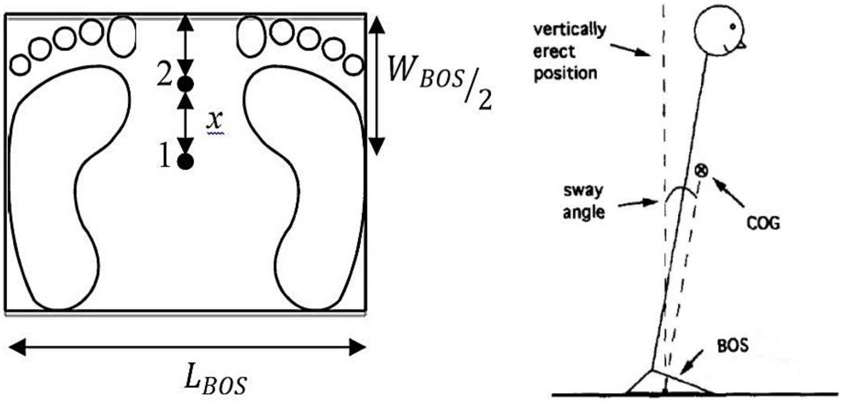

Figure 1: Parameters of the sway of the body.

appropriate solutions on changing the work condition or changing the BOS or wearing shoes can be recommended).

Parameter	Range	Step
Height	165-185 cm	1 cm
Anterior sway angle	2.5-6.0°	0.5°
Posterior sway angle	3.5-7.0°	0.5°
Medio-lateral sway angle	6.0-9.5°	0.5°
COG% index	50-70%	50%

Table 1: Parameters range.

BOS dimensions	Relationship
BOS Width	0.152 × H
BOS Length	(0.055 + 0.191) × H

Table 2: BOS calculations.

Parameters setting

In order to arrange the settings, parameters' range must be defined. So, based on the average of various studies, the ranges in Table 1 are considered for height, sway angle and COG% [23,29].

In addition, in order to obtain the BOS dimensions, we use biometric relationships between body height and other body part dimensions [30]. The BOS relationships, used in this study, are presented in Table 2. In these statements, H represents height of the person.

Also, as the height of COG in normal human is 57% of his height, Equation 2 calculates the variable in Equation 1.

$$X=(H_{COG})\times\tan(Angle_{s}) \quad (2)$$

Where H_{COG} and $Angle_{s}$ are the COG height and Sway angle, respectively.

Static stability results

A sample of the tabular results, based on parameters range and relations, is presented in Table 3. It is populated for the height of 170 cm and anterior sway.

It's shown in Table 3 that if a person with 170 cm height and 29 cm BOS width sway 4° in anterior direction, his COG% will be 46.73%; while the same person will obtain 70.24% if he can sway 6° in same direction. When the sway angle increases, balance control becomes harder and if someone can keep his balance in higher sway angles, his COG% will increase which shows his ability to keep the balance. It is also shown that for a person with specific height in a fixed sway angle, the smaller the BOS width, the higher the COG% which again means his ability to maintain his balance.

Another way of result comparison can be as Table 4. It is developed for COG%=60%. It can be inferred from this table that a particular person having a certain COG% in higher sway angles, needs larger BOS dimensions.

Dynamic Stability

Methods

One of the well-known indices in dynamic stability is maximum lyapunov exponent (λ_{max}) which was presented by Aleksandr Lyapunov in 1892 [27]. The concept of stability in Lyapunov theory is that if all the paths which start around an equilibrium point remain in a neighbourhood of that point for all time intervals, that point is stable in Lyapunov concept [31]. In mathematics, the Lyapunov exponent of a dynamical system is a quantity that characterizes the rate of separation of infinitesimally close trajectories. Quantitatively, two trajectories in phase space with initial separation δZ_0 diverge at a rate given by Equation 3.

$$|\delta Z_{(t)}| \approx e^{\lambda t}|\delta Z_{0}| \quad (3)$$

The rate of separation can be different for different orientations of initial separation vector. Thus, there is a spectrum of Lyapunov exponents, equal in number to the dimensionality of the phase space. It is common to refer to the largest one as the maximal Lyapunov exponent (MLE) which is defined by Equation 4.

$$\lambda_{max}=\lim_{(t\to\infty)}\lim_{(\delta Z\_0\to 0)} (1/t \ \ln|\delta Z_{((t))}| /\delta Z_{0}| \quad (4)$$

The maximum Lyapunov exponent is a measure of local stability. Large exponents indicate rapid divergence of two points that are initially close in state space. By calculating the maximum Lyapunov exponent from data that is averaged over the entire time series, the global stability of the system is estimated [28].

A positive MLE is usually taken as an indication that the system is chaotic. This index is selected for the experimental tests of this study. In order to calculate this index, a program is written in Matlab R2010b with the Algorithm 1.

BOS Width	**Sway angle (°)**							
	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
30.50	27.74	33.30	38.86	44.43	50.01	55.59	61.18	66.78
30.00	28.20	33.86	39.51	45.17	50.84	56.52	62.20	67.90
29.50	28.68	34.43	40.18	45.94	51.70	57.48	63.26	69.05
29.00	29.18	35.02	40.87	46.73	52.59	58.47	64.35	70.24
28.50	29.69	35.64	41.59	47.55	53.52	59.49	65.48	71.47
28.00	30.22	36.27	42.33	48.40	54.47	60.55	66.65	72.75
27.50	30.77	36.93	43.10	49.28	55.46	61.66	67.86	74.07
27.00	31.34	37.62	43.90	50.19	56.49	62.80	69.11	75.44
26.50	31.93	38.33	44.73	51.14	57.56	63.98	70.42	76.86
26.00	32.54	39.06	45.59	52.12	58.66	65.21	71.77	78.34
25.50	33.18	39.83	46.48	53.14	59.81	66.49	73.18	79.88
25.00	33.85	40.63	47.41	54.21	61.01	67.82	74.64	81.48
24.50	34.54	41.46	48.38	55.31	62.25	69.21	76.17	83.14
24.00	35.26	42.32	49.39	56.47	63.55	70.65	77.75	84.87
23.50	36.01	43.22	50.44	57.67	64.90	72.15	79.41	86.68
23.00	36.79	44.16	51.54	58.92	66.31	73.72	81.13	88.56
22.50	37.61	45.14	52.68	60.23	67.79	75.36	82.94	90.53
22.00	38.46	46.17	53.88	61.60	69.33	77.07	84.82	92.59
21.50	39.36	47.24	55.13	63.03	70.94	78.86	86.79	94.74
21.00	40.29	48.36	56.44	64.53	72.63	80.74	88.86	97.00

Table 3: COG% for different settings.

Sway angle (°)		**Height (cm)**	**165**	**167**	**169**	**170**	**173**	**175**	**177**	**179**	**180**	**183**	**185**
Anterior	2.5	BOS Width	13.692	13.857	14.02	14.105	14.355	14.518	14.687	14.853	14.934	15.185	15.35
	3.0		16.432	16.632	16.831	16.93	17.23	17.427	17.627	17.827	17.925	18.226	18.423
	3.5		19.177	19.409	19.642	19.759	20.106	20.339	20.57	20.804	20.919	21.269	21.499
	4.0		21.924	22.19	22.454	22.588	22.985	23.253	23.517	23.785	23.916	24.316	24.581
	4.5		24.675	24.973	25.274	25.422	25.871	26.17	26.468	26.769	26.917	27.366	27.666
	5.0		27.429	27.762	28.094	28.261	28.76	29.091	29.424	29.757	29.922	30.421	30.754
	5.5		30.189	30.553	30.92	31.103	31.652	32.016	32.383	32.75	32.932	33.48	33.847
	6.0		32.951	33.351	33.751	33.949	34.548	34.948	35.348	35.748	35.946	36.545	36.945
Posterior	3.5	BOS Width	19.177	19.409	19.642	19.759	20.106	20.339	20.57	20.804	20.919	21.269	21.499
	4.0		21.924	22.19	22.454	22.588	22.985	23.253	23.517	23.785	23.916	24.316	24.581
	4.5		24.675	24.973	25.274	25.422	25.871	26.17	26.468	26.769	26.917	27.366	27.666
	5.0		27.429	27.762	28.094	28.261	28.76	29.091	29.424	29.757	29.922	30.421	30.754
	5.5		30.189	30.553	30.92	31.103	31.652	32.016	32.383	32.75	32.932	33.48	33.847
	6.0		32.951	33.351	33.751	33.949	34.548	34.948	35.348	35.748	35.946	36.545	36.945
	6.5		35.721	36.153	36.586	36.803	37.451	37.885	38.318	38.751	38.966	39.617	40.049
	7.0		38.493	38.96	39.427	39.661	40.361	40.827	41.294	41.761	41.992	42.694	43.16
Medio-Lateral	6.0	BOS Length	32.951	33.351	33.751	33.949	34.548	34.948	35.348	35.748	35.946	36.545	36.945
	6.5		35.721	36.153	36.586	36.803	37.451	37.885	38.318	38.751	38.966	39.617	40.049
	7.0		38.493	38.96	39.427	39.661	40.361	40.827	41.294	41.761	41.992	42.694	43.16
	7.5		41.275	41.775	42.275	42.524	43.276	43.776	44.276	44.776	45.025	45.777	46.277
	8.0		44.06	44.594	45.129	45.396	46.197	46.731	47.265	47.799	48.066	48.867	49.401
	8.5		46.854	47.422	47.989	48.274	49.125	49.694	50.262	50.829	51.113	51.964	52.532
	9.0		49.655	50.257	50.858	51.159	52.061	52.664	53.266	53.867	54.169	55.071	55.673
	9.5		52.462	53.099	53.735	54.052	55.006	55.642	56.278	56.914	57.232	58.186	58.822

Table 4: BOS dimensions for COG%=60%.

```
A=xlsread('file name.xls')
B=matrix of the time series data (selected cells of A)
Neighbor_i=[] % n×2 matrix of distances between point i and all other points
Distances=[] % n×n matrix of distances between each 2 points
NearestNeighbors=[] % 3n×3 matrix of 3 nearest neighbors of each point
For i=1:n
    For j=1:n
        Calculates the distances between each point i and all other points
        Finds the first nearest neighbor (non-zero distance) of point i in Neighbor_i.
    End
    For j=1:n
        Finds the second nearest neighbor (non-zero distance) of point i in Neighbor_i
    End
    For j=1:n
        Finds the third nearest neighbor (non-zero distance) of point i in Neighbor_i
    End
    Distances matrix is prepared from Neighbor_i matrixes
    Nearest Neighbors matrix is prepared from first 3 nearest neighbors of each point i
End
For t=1:3*(n-1)
    For each row of the Nearest Neighbors matrix as a reference point, calculates the distance between this point and each nearest neighbor as both points evolve over time
    The expansion is defined as the relative increase in distance between the two points for some $\Delta t$.
End
The mean expansion is determined by averaging the expansion over all reference points and all nearest neighbors. Lyapunov Exponent is calculated from the mean expansion
```

Algorithm 1: Calculating maximum lyapunov exponent.

Participants

Twelve healthy volunteers, 6 males and 6 females, participated in the tests. The age, height and weight ranges of the subjects are presented in Table 5.

Apparatus

The gait analyzer treadmill from the German company SCHEIN with the analysis system of Zebris FDM-T is used in the tests. This device measures the dynamic pressure and force and analyses the pressure distribution in standing, walking and running. In addition, this device lets us adjust the angle instead of measuring it by goniometer so we can do the test while increasing or decreasing the angle.

The data obtained from the treadmill are complete time series of the pressure, force, area and location of COP for each feet. In addition, the time series data on each cell of the treadmill surface can be obtained by programming the original data. Therefore, we can use the time series of force and the COP location of both feet in order to calculate the maximum Lyapunov exponent.

Protocol

Subjects were asked to stand on the treadmill surface and keep the feet fully in contact with the surface throughout the tests. They were instructed to stand with their feet in a comfortable position, which was approximately separated equal to hip width and their hands at body sides without any loads. They could rotate only about the ankles. The difference between tests was in the directions and magnitude of the sway angles. In addition, as people usually have safety shoes while working in industrial sites, in these tests, the effect of shoes on stability is investigated. The shoes affect the BOS dimensions. Hence all the tests on each subject were done twice; once without shoes and once wearing safety shoes. Each subject performed 16 tests as per Figure 2.

Subjects	Age range (years)	Height range (cm)	Weight range (kg)
6 female	28 ± 3	160.50 ± 10.50	59.10 ± 11.90
6 male	28 ± 3	179.75 ± 7.25	80.50 ± 13.40
Average for all	28 ± 3	168.50 ± 18.50	70.55 ± 23.35

Table 5: Participants' specifications.

In "0-8° Sway" test, the angle of the treadmill surface is increased from 0-8° in 35 s while the subject is standing anteriorly on it and trying to keep his balance. The "Without Sway" test is the test of standing still on the horizontal surface for 5 s and the "Fixed Sway" tests are the tests of standing on the inclined surface in corresponding direction for 5 s. The frequency of treadmill motion was adjusted on 50 Hz.

Experimental results

The software of the treadmill divides the surface to 128 lines and 56 columns (each cell 8.5*8.5 mm2) and the force and pressure of each cell is recorded in each time interval. The total BOS area can also be calculated in each time interval so that the BOS length and width can be achieved.

After each test, the max Lyapunov exponent was calculated for COP location and force time series. Results of tests on 6 male participants without shoes are as listed in Table 6.

According to the comparison between the result tables of the two types of tests (without shoes and wearing shoes), λ_{max} for COP and total force has decreased in 53 and 54% of the tests, respectively. Also if we consider the fixed sway tests, the λ_{max} for COP has decreased in 7 out of 12 subjects of anterior tests, 6 out of 12 subjects of posterior tests and 6 out of 12 subjects of medio-lateral tests. This analysis for the λ_{max} for force shows 8, 3 and 6 out of 12 subjects, respectively.

Based on the above analysis, we can conclude that wearing safety shoes, in about 50% of times will improve stability of the person.

Comparison of Static and Dynamic Stability

In order to compare the results of dynamic stability with static stability in previous sections, Table 7 is presented for four participants. It must be noticed that wearing shoes slightly change the height and weight of the person.

In Table 7, it is shown that by increasing the sway angle in every direction, the COG% increases which show the person had better postural stability. Meanwhile, the results of dynamic stability in same situation show that by increasing the sway angle in every direction, λ_{max} related to COP shows a chaos in the COP path which needs more effort of the person to maintain stability. This means he has better ability of stability maintenance. In fact, the comparison of results reveals that in spite of the fact that there is no specific mathematical relation between COG% and λ_{max}, these two indices have direct relation to each other.

Conclusion

For many occupational tasks like working on pylons or Scaffolds, postural stability is highly important. In this study, static and dynamic stability were studied in relation to COG and other anthropometric characteristics. In static stability, the effect of anthropometric factors on COG% between 50-70%, height range of 165-185 cm, postural sways of 2.5-6.0° anterior, 3.5-7.0° posterior and 6.0-9.5° medio-lateral were investigated. It showed that a person with certain height and BOS dimensions can sway higher angles and have better ability to maintain stability. For a certain height, in a fixed angle, smaller BOS dimensions cause higher COG% which shows better stability maintenance. Also, a person who maintains a certain COG% in higher sway angles, must have larger BOS dimensions.

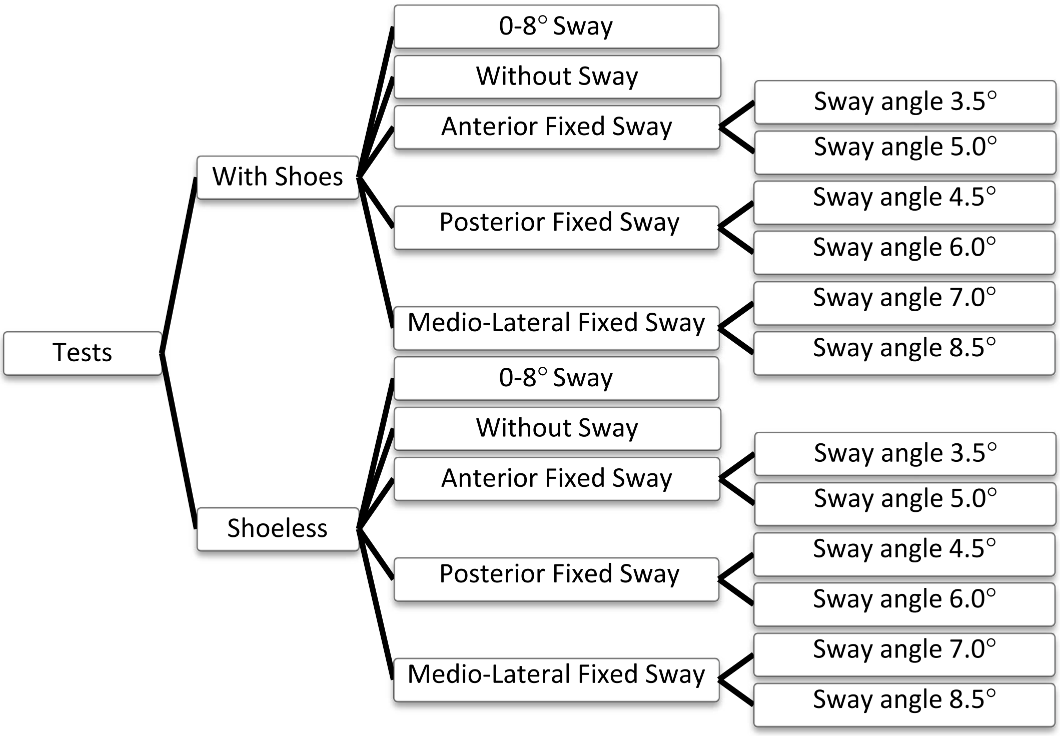

Figure 2: Different setting for dynamic stability tests.

Participant number	Subject Info	Test type	Without Sway	Fixed Sway					
				3.5° A	5.0° A	4.5° P	6.0° P	7.0° M-L	8.5° M-L
1	Height=178 cm Weight=88 kg	BOS Length (cm)	34.72	33.88	33.88	33.03	32.18	37.26	37.26
		BOS Width (cm)	25.41	25.41	24.56	23.71	25.41	22.87	26.25
		λ_{max} for COP	132.78	58.99	105.69	63.22	66.60	73.48	99.05
		λ_{max} for Force	152.60	142.13	155.66	145.15	142.93	147.91	186.35
2	Height=173 cm Weight=68 kg	BOS Length (cm)	38.11	34.72	33.88	34.72	34.72	38.96	38.11
		BOS Width (cm)	24.56	24.56	25.41	23.71	24.56	23.71	24.56
		λ_{max} for COP	105.84	105.63	98.89	91.45	108.34	81.55	92.99
		λ_{max} for Force	152.75	127.79	132.42	175.12	137.62	146.55	134.07
3	Height=179 cm Weight=72 kg	BOS Length (cm)	34.72	34.72	34.72	35.57	36.42	34.72	36.42
		BOS Width (cm)	25.41	24.56	24.56	25.41	26.25	24.56	23.71
		λ_{max} for COP	82.30	93.43	109.50	69.46	41.97	103.17	51.24
		λ_{max} for Force	157.49	142.46	153.20	139.11	134.80	162.58	147.51
4	Height=174 cm Weight=67.1 kg	BOS Length (cm)	37.26	37.26	37.26	36.42	38.11	38.11	36.42
		BOS Width (cm)	23.71	24.56	24.56	25.41	25.41	22.87	23.71
		λ_{max} for COP	97.77	119.71	112.69	97.82	142.15	79.55	107.76
		λ_{max} for Force	139.44	129.66	124.04	158.18	142.06	142.25	160.11
5	Height=180 cm Weight=76 kg	BOS Length (cm)	33.88	33.88	33.03	34.72	34.72	34.72	34.72
		BOS Width (cm)	27.10	26.25	26.25	26.25	26.25	25.41	25.41
		λ_{max} for COP	83.57	138.54	67.41	102.33	69.73	80.59	83.92
		λ_{max} for Force	155.54	131.77	139.03	131.93	132.51	139.77	158.03
6	Height=187 cm Weight=93.9 kg	BOS Length (cm)	33.03	38.11	37.26	34.72	35.57	38.11	38.11
		BOS Width (cm)	29.64	29.64	29.64	29.64	29.64	28.79	27.95
		λ_{max} for COP	82.18	171.18	87.50	65.53	87.80	97.61	116.04
		λ_{max} for Force	159.13	195.29	145.40	180.95	158.76	153.97	167.14

Table 6: Experimental results for male participants (without shoes).

Participant id	Test type	Height (cm)	Sway Angle & Direction	3.5° A	5.0° A	4.5° P	6.0° P	7.0° M-L	8.5° M-L
A	Without Shoes	173	BOS Length (cm)	34.72	33.88	34.72	34.72	38.96	38.11
			BOS Width (cm)	24.56	25.41	23.71	24.56	23.71	24.56
			λ_{max} for COP	105.63	98.89	91.45	108.34	81.55	62.99
			COG%	49.12%	67.91%	65.46%	84.41%	62.16%	77.34%
	With Shoes	176	BOS Length (cm)	38.11	37.26	37.26	36.42	38.11	38.11
			BOS Width (cm)	21.17	21.17	22.02	22.02	21.17	22.87
			λ_{max} for COP	98.53	80.27	61.65	90.09	103.36	92.3
			COG%	57.97%	82.93%	71.71%	95.77%	64.65%	78.68%
B	Without Shoes	178	BOS Length (cm)	33.88	33.88	33.03	32.18	37.26	37.26
			BOS Width (cm)	25.41	24.56	23.71	25.41	22.87	26.25
			λ_{max} for COP	58.99	105.69	63.22	66.60	73.48	99.05
			COG%	48.85%	72.29%	67.36%	83.95%	66.87%	81.39%
	With Shoes	181	BOS Length (cm)	37.26	37.26	39.80	36.42	35.57	35.57
			BOS Width (cm)	22.02	22.02	22.87	22.87	23.71	23.71
			λ_{max} for COP	113.16	93.82	99.03	95.70	107.85	81.58
			COG%	57.31%	81.98%	71.01%	94.84%	71.23%	86.70%
C	Without Shoes	179	BOS Length (cm)	34.72	34.72	35.57	36.42	34.72	36.42
			BOS Width (cm)	24.56	24.56	25.41	26.25	24.56	23.71
			λ_{max} for COP	93.43	109.5	69.46	41.97	10.3.17	51.24
			COG%	50.82%	72.69%	63.21%	81.71%	72.17%	83.74%
	With Shoes	182	BOS Length (cm)	34.72	34.72	37.26	35.57	35.57	36.42
			BOS Width (cm)	21.17	22.02	23.71	22.87	22.02	22.02
			λ_{max} for COP	52.73	140.14	125.63	150.83	81.78	79.06
			COG%	59.95%	82.44%	68.88%	95.36%	71.62%	85.14%
D	Without Shoes	180	BOS Length (cm)	33.88	33.03	34.72	34.72	34.73	34.72
			BOS Width (cm)	26.25	26.25	26.25	26.25	25.41	25.41
			λ_{max} for COP	138.54	67.41	102.33	69.73	80.59	83.92
			COG%	47.82%	68.4%	61.53%	82.17%	72.57%	88.33%
	With Shoes	183	BOS Length (cm)	33.03	33.03	33.88	33.88	34.72	34.72
			BOS Width (cm)	22.02	22.87	22.02	22.87	22.87	22.02
			λ_{max} for COP	109.13	114.97	110.15	68.37	91.72	87.54
			COG%	57.95%	79.81%	74.56%	95.88%	73.78%	89.8%

Table 7: Comparison of results.

For dynamic stability, Liapunov exponent and λ_{max} index were used to assess the stability of different postural sway positions. Anthropometric factors and experimental tests on gait analyzer treadmill were collected to obtain the results. The tests were performed on 12 participants with and without shoes and in different sway angles.

The comparisons of the results in static and dynamic analysis in fixed sway shows that by increasing the sway angle in every direction, COG% increased which indicates the better postural stability. This is while the results of dynamic stability in same situation also show that by increasing the sway angle in every direction, the chaos in the COP path is increased which needs more effort of the person to maintain stability. So a relationship between static and dynamic stability is evident. In addition, the result of wearing safety shoes in dynamic stability is that in 50% of times, it will improve stability.

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