

## ORIGINAL ARTICLE

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## TEST-RETEST RELIABILITY OF WAVELET-BASED SPECIFIC FREQUENCY BANDS OF POSTURAL CONTROL DURING TWO STANDING TASK CONDITIONS

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## ABSTRACT

**Background:** The evaluation of balance measures can help identify postural control processes, but traditional data collection for the center of pressure (COP) may not reveal differences in postural control mechanisms. This study aimed to evaluate the reliability of the frequency component of postural sway using wavelet analysis of COP signals.

**Methods:** Fifteen healthy male subjects (average age:  $39.16 \pm 7.2$  years, average weight:  $72 \pm 11.06$  kg, average height:  $171 \pm 6.31$  cm) participated in this project. They were requested to perform three trials of single-leg and tandem stance conditions for 20-second with and without vision on a force plate. The frequency content of COP signals, including the energy, root mean square (RMS), and velocity of the COP in four frequency bandwidths of postural sway, was evaluated. The test-retest reliability of COP parameters was tested using the intraclass correlation coefficient (ICC).

**Results:** Among different COP parameters, the energy of the COP within a moderate (1.56–6.25 Hz) frequency band ( $.79 \leq \text{ICC} \leq .97$ ) with standard error measurement (SEM) ranged from .14 to .23, the RMS of COP within low (.39–1.56 Hz) ( $.79 \leq \text{ICC} \leq .93$ ) and ultralow ( $< .10$  Hz) (SEM ranged from .000 to .002) ( $.78 \leq \text{ICC} \leq .94$ ) in a tandem stance and the RMS of COP in a bandwidth of  $< .10$  Hz (SEM=.00) in a single-leg stance ( $.70 \leq \text{ICC} \leq .99$ ) with the eyes closed and open showed good to excellent reliability.

**Conclusion:** The results of this study showed moderate to excellent reliability of wavelet-based COP measures; therefore, these parameters can be used for the identification of postural control mechanisms.

**Keywords:** Postural control; Center of pressure; Reliability; Frequency content.

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## INTRODUCTION

One of the common evaluating methods of the postural control system is assessing the center of pressure (COP) variables [1,2]. Information extracted from COP measures can be worthwhile in the identification of a postural control deficiency [3]. The different contexts of balance, such as sensory input, environment, and health-related levels, affect postural control measures. COP displacements are exploratory and provide information about the environment where subjects are moving [4]. Thus, any changes in postural stability affect these exploratory behaviors and responses of the postural system in a dynamically unfolding environment [5]. However, the choice of suitable balance variables is essential for dysfunction classification and diagnosis and monitoring rehabilitation [6].

The analysis of balance measures can help identify postural control processes. Still, traditional data collection for the COP, such as displacement, velocity, and standard deviation, may not reveal differences in postural control mechanisms [7]. Therefore, finding the analytical methods of extracting COP data to capture the richness of balance data accurately can be useful to identify postural control processes. Because of the dynamic nature of COP signals, it is difficult to interpret information through traditional balance variables [8].

One postural sway decomposition measure is the specific frequency band of the COP. Different sensorimotor systems interactions maintain an upright posture. COP signals include several frequency components, and every frequency band represents a specific sensorimotor activation [5].

One of the modern analytical methods that decompose COP data into several frequency bands is wavelet analysis. This decomposition method of postural sway is helpful to reveal the shift mechanism of sensorimotor systems, while it is not obtained through traditional parameters of postural control [9]. Therefore, postural control strategies may be identified with wavelet analysis in different neuromuscular disorders.

Wavelet analysis decomposes COP signals into four frequency bands; each band is a representation of visual, vestibular, cerebellum, and proprioception activation. Wavelet analysis was shown to be more sensitive to detect insufficiencies in postural stability in patients with whiplash-associated disorders compared to traditional analysis methods [10]. This analysis can be useful to evaluate the contribution of sensory and central components of postural behavior.

The purpose of this study is to examine the reliability of COP signal frequency bandwidths in two standing task conditions.

## METHODS

### Study design and participants

Fifteen healthy male subjects participated in the

experiment. Their average (SD) age, height, and body mass were 39.16 (7.2) years, 171 (6.31) cm, and 72 (11.06) kg, respectively. Participants were recruited through printed advertisements and word of mouth.

Exclusion criteria included: recent lower extremity injury (<1 year), current lower extremity pain, previous lower extremity fracture, balance dysfunctions (e.g., vestibular conditions), medications affecting balance, and neurological disorders. Written informed consent was obtained from participants, and the study was approved by the Iran University of medical sciences ethics board (IR.IUMS.REC13959211342210). None of the subjects reported any neural or musculoskeletal dysfunctions. Female participants were not included in this research, in an attempt to minimize potential gender differences.

### Ethical approval

Each subject gave signed informed consent and was allowed to withdraw from the study at any time. This study has been approved by the ethics review board of Iran University of Medical Sciences, with permission number IR.IUMS.REC 1395.9211342210.

## PROCEDURE

A force plate (Kistler 9260AA6, Kistler instrument AG, Winterthur Switzerland) with a sampling frequency of 100 Hz was used.

Subjects were asked to perform two standing posture positions barefoot on a force plate with their eyes closed (EC) or opened (EO). Participants performed three trials of 20-s single-leg quiet standing with their arms by their side on the preferred leg. Participants were instructed to maintain the contralateral limb (non-stance limb) at 30° of the knee and hip flexion. Subjects also performed three trials in the tandem position for 20-s with a short rest in between. In this task, subjects stood on a force plate in which one lower extremity was placed on the back of others. The order of task performance and the opening or closing of the eyes was random. Subjects were asked to standing upright and look straight at eye level in a standardized position approximately four meters away.

To ensure the same feet placement for repeated trials, feet positions were traced on paper. During the task performance, if there was a displacement of feet on paper, the test was repeated. Ten days later, analyses were repeated by subjects to obtain inter-session reliability for the frequency band of COP signals. All procedures were conducted by the same physiotherapist, in the same environment, and at the same time of day to ensure uniformity.

### Data analysis

The wavelet analysis decomposed the COP signals to four frequency components: (1) moderate (1.56–6.25 Hz), (2) low (0.39–1.56 Hz), (3) very low (0.10–0.39 Hz), and (4) ultralow (<0.10 Hz). These frequency components are hypothesized to capture postural movements associated with (1) spinal reflexive loops and muscle activity [11], (2) cerebellar [12] (3) vestibular [13], and (4) visual systems

[14,15] respectively. Energy (intensity), RMS, and the velocity of the COP in frequency bands were assessed. Measures were examined in anteroposterior (AP) and mediolateral (ML) directions and with the eyes open or closed.

The abovementioned outcome measures were also evaluated independently in four distinct bandwidths of the signal frequency. The bandwidths were separated using a nine-level Symlet-8 wavelet, with the multi-resolution analysis used to combine the detail levels to achieve the respective frequency bands.

### Statistical analyses

Statistical analyses were performed using SPSS Statistics for Windows, version 22 (SPSS Inc, Chicago, IL, USA). The mean of three trials of the COP parameters in each condition was used for statistical analysis to determine reliability measures.

Relative reliability was investigated with the intraclass correlation coefficient (ICC) (3, K) on the average score method. The significance level for all the tests was set at  $P \leq .05$ . The evaluation of the ICC was based on the recommendation of Koo (Koo & Li 2016). ICC scores were categorized as follows: excellent (0.90–1), good (0.75–0.89), moderate (0.50–0.75), and poor (0–0.49). The standard error measurement (SEM) was calculated as the standard deviation of the difference between two scores; this method was selected to avoid the influence of sample heterogeneity and to reduce the effect of systematic error. The SEM and the 95% CI of ICC values were also calculated for all dependent variables. The use of the 95% CI demonstrates how closely the measurements are

in agreement on different occasions, whereas the SEM indicates the precision of measurements.

### RESULTS

The results of ICC values for wavelet-based COP measures in two postural stances are presented in Tables 2 and 3. The tandem stance had ICC values greater than .87 for the energy of COP with the eyes closed in the ML direction.

The energy of COP signals in the medium frequency band with the eyes closed and open in ML and AP directions showed good to excellent reliability in the tandem stance condition ( $ICC \geq .79$ ).

The RMS of COP in all four frequency bandwidths in the single-leg stance condition in the ML direction had reliability greater than .61, while these ICC values were greater than .78 in the tandem stance condition.

Except for velocity in the very-low-frequency band with the eyes closed, the ICC values of COP velocity were  $\geq .85$  (good and excellent reliability) for the other three frequency bands with the eyes closed in AP directions in the tandem stance.

The velocity of COP signals in moderate and ultralow frequency bands in a single-leg stance with the eyes open in the ML direction showed  $ICC = .47$  and  $.48$ , respectively (poor reliability).

**Table 1:** Demographic data of the subjects

Variables	N= 15
Age, years, mean (SD)	39.16 (7.2)
Height, cm, mean (SD)	171 (6.31)
Weight, kg, mean (SD)	72 (11.06)

**Table 2:** Test-retest reliability analysis of frequency bands of COP measures in Single leg stance

Parameters	Test	Retest		ICC (95%CI)		SEM		MDC			
		EC	EO	EC	EO	EC	EO	EC	EO		
FQ energy (%)	AP	EC	EO	EC	EO	EC	EO	EC	EO		
	ML	EC	EO	EC	EO	EC	EO	EC	EO		
1.56<FQ<6.25	AP	6.533(4.989)	2.720(1.112)	6.464(4.987)	2.927(1.393)	.97(.93-.99)	.81(.43-.93)	.15	.42	.41	1.16
	ML	3.51(1.22)	1.310(.642)	3.27(1.30)	1.703(.883)	.77(.33-.92)	.61(-.13-.87)	.61	.41	1.69	1.13
0.39<FQ<1.56	AP	41.398	30.658(8.620)	42.128(9.722)	32.941(10.465)	.82(.48-.94)	.67(.04-.89)	2.61	5.35	7.23	14.82
	ML	27.46(9.957)	16.881(9.837)	23.870(8.558)	19.244(9.556)	.82(.47-.94)	.85(.56-.95)	2.69	3.24	7.45	8.98
0.10<FQ<0.39	AP	19.308(9.667)	11.792(2.930)	20.345(12.235)	11.955(4.078)	.85(.55-.95)	.46(-.59-.82)	2.32	3.59	6.43	9.95
	ML	22.920(6.920)	11.837(2.974)	22.552(9.293)	13.124(4.937)	.77(.31-.92)	.76(.29-.92)	2.77	2.90	7.67	8.03
<.10	AP	32.832(10.985)	54.828(8.581)	30.374(11.517)	52.174(9.809)	.76(.29-.92)	.25(-1.20-.75)	4.14	12.30	11.47	34.09
	ML	46.952(12.890)	70.063(11.430)	50.198(16.365)	65.908(13.152)	.85(.57-.95)	.67(.02-.89)	3.82	8.57	10.58	23.75
<b>RMS (cm)</b>											
1.56<F<6.25	AP	.005(.003)	.002(.000)	.006(.003)	.002(.000)	.96(.90-.98)	.74(.25-.91)	.00	.00	0	0
	ML	.006(1.22)	.001(.000)	.006(.011)	.001(.000)	.99(.99-.99)	.64(-.04-.88)	.00	.00	0	0
.39<F<1.56	AP	.014(.002)	.007(.000)	.013(.002)	.007(.001)	.30(-1.07-.76)	.74(.25-.91)	.00	.00	0	0
	ML	.013(.005)	.005(.000)	.011(.005)	.005(.000)	.93(.79-.97)	.74(.24-.91)	.00	.00	0	0
.10<F<.39	AP	.008(.001)	.004(.000)	.008(.001)	.004(.001)	.85(.55-.95)	.71(.10-.90)	.00	.00	0	0
	ML	.013(.009)	.004(.001)	.012(.010)	.004(.000)	.97(.93-.99)	.61(-.14-.87)	.00	.00	0	0
<.10	AP	.014(.006)	.010(.002)	.011(.006)	.009(.002)	.84(.52-.94)	.72(.17-.90)	.00	.00	0	0
	ML	.026(.007)	.013(.003)	.025(.041)	.011(.003)	.99(.99-1.00)	.70(.12-.90)	.00	.00	0	0
<b>Velocity (cm/s)</b>											
1.56<F<6.25	AP	5.415(2.831)	2.045(.557)	4.951(2.906)	2.109(.633)	.95(.87-.98)	.69(.09-.89)	.09	.13	.24	.36
	ML	3.33(.55)	1.688(.181)	2.68(.74)	1.804(.445)	.96(.87-.98)	.47(-.57-.82)	.13	.16	.36	.44
.39<F<1.56	AP	4.895(.736)	2.432(.344)	4.573(.957)	2.570(.501)	.53(-.38-.84)	.84(.54-.94)	.26	.09	.72	.24
	ML	4.294(1.091)	1.742(.308)	3.566(1.023)	1.781(.409)	.79(.39-.93)	.90(.71-.96)	.27	.06	.74	.16
.10<F<.39	AP	.586(.090)	.282(.058)	.542(.097)	.298(.083)	.84(.52-.94)	.74(.23-.91)	.00	.03	.00	.08
	ML	.907(.526)	.322(.078)	.849(.541)	.322(.050)	.96(.89-.98)	.66(.01-.88)	.02	.00	.05	.00
<.10	AP	.298(.069)	.201(.049)	.248(.102)	.186(.034)	.68(.07-.89)	.73(.19-.90)	.02	.02	.05	.05
	ML	.502(.596)	.262(.045)	.458(.611)	.235(.058)	.99(.97-.99)	.48(-.54-.82)	.00	.05	.00	.13

COP: Center of pressure; FQ: Frequency; RMS: Root mean square; EO: Eyes open; EC: Eyes closed; ICC: Intraclass correlation coefficient; 95%CI: 95% confidence interval; AP: Anteroposterior; ML: Mediolateral; SEM: Standard error measurement; MDC: Minimal detectable change

**Table 3:** Test-retest reliability analysis of frequency bands of COP measures in Tandem stance

Parameters		Test		Retest		ICC (95%CI)		SEM		MDC	
FQ energy (%)		EC	EO	EC	EO	EC	EO	EC	EO	EC	EO
1.56<FQ<6.25	AP	2.486(1.666)	.704(.390)	2.660(1.392)	1.194(.687)	.97(.93-.99)	.81(.63-.91)	.239	.140	.66	.38
	ML	3.789(2.001)	1.592(.640)	4.225(2.502)	2.233(1.164)	.96(.89-.98)	.79(.40-.93)	.218	.219	.60	.60
0.39<FQ<1.56	AP	31.641(10.551)	16.646(7.015)	34.682(6.775)	22.752(10.13)	.48(-.55-.82)	.56(-.29-.85)	7.07	4.052	19.59	11.23
	ML	30.816(14.358)	19.918(7.883)	29.958(13.745)	20.824(7.563)	.89(.68-.96)	.53(-.39-.84)	2.87	2.73	7.95	7.56
0.10<FQ<0.39	AP	17.285(3.850)	12.367(6.165)	19.463(5.448)	16.136(5.422)	.34(-.94-.78)	.76(.30-.92)	6.62	3.40	18.34	9.42
	ML	14.034(7.732)	9.063(3.952)	11.654(7.959)	8.051(2.413)	.94(.84-.98)	.66(.00-.88)	4.65	2.85	12.88	7.89
<.10	AP	48.569(11.341)	70.172(9.888)	43.193(6.116)	59.911(14.041)	.49(-.50-.83)	.56(-.29-.85)	8.74	7.45	24.22	20.65
	ML	51.334(13.488)	69.942(10.555)	54.144(14.192)	68.871(8.607)	.87(.61-.95)	.64(-.06-.88)	6.54	7.67	18.12	21.26
RMS (cm)											
1.56<F<6.25	AP	.002(.000)	.001(.000)	.002(.000)	.001(.000)	.90(.71-.96)	.87(.62-.95)	.00	.00	0	0
	ML	.002(.001)	.000(.000)	.002(.000)	.000(.000)	.96(.88-.98)	.80(.41-.93)	.00	.00	0	0
.39<F<1.56	AP	.104(.002)	.005(.001)	.104(.002)	.005(.001)	.86(.58-.95)	.79(.37-.93)	.000	.000	0	0
	ML	.007(.003)	.004(.001)	.006(.002)	.004(.001)	.93(.80-.97)	.79(.38-.93)	.00	.00	0	0
.10<F<.39	AP	.007(.001)	.004(.001)	.007(.002)	.004(.001)	.59(-.22-.86)	.66(-.01-.88)	.001	.000	0	0
	ML	.005(.003)	.003(.001)	.004(.002)	.002(.001)	.94(.82-.98)	.90(.70-.96)	.00	.00	0	0
<.10	AP	.014(.003)	.012(.002)	.012(.002)	.010(.003)	.79(.38-.93)	.78(.37-.92)	.001	.002	0	0
	ML	.011(.006)	.009(.006)	.010(.005)	.009(.003)	.94(.83-.98)	.78(.37-.92)	.00	.00	0	0
Velocity (cm/s)											
1.56<F<6.25	AP	2.433(1.050)	1.048(.350)	2.392(.740)	1.153(.306)	.91(.74-.97)	.87(.62-.95)	.096	.046	.24	.11
	ML	2.874(1.253)	1.253(.384)	2.860(1.002)	1.411(.501)	.95(.85-.98)	.39(-.81-.79)	.07	.08	.19	.22
.39<F<1.56	AP	3.383(.988)	1.661(.546)	3.324(.845)	1.746(.319)	.85(.55-.95)	.66(.00-.88)	.197	.040	.52	.11
	ML	2.571(1.169)	1.276(.455)	2.490(.947)	1.466(.396)	.96(.90-.98)	.72(.18-.90)	.17	.07	.47	.19
.10<F<.39	AP	.531(.090)	.316(.087)	.498(.145)	.315(.082)	.47(-.58-.82)	.76(.30-.92)	.106	.079	.27	.19
	ML	.350(.184)	.216(.097)	.304(.162)	.194(.068)	.92(.78-.98)	.90(.70-.96)	.13	.09	.36	.24
<.10	AP	.327(.083)	.248(.058)	.286(.084)	.211(.069)	.96(.88-.98)	.57(-.26-.85)	.192	.032	.52	.08
	ML	.215(.101)	.174(.079)	.220(.114)	.163(.050)	.86(.60-.95)	.84(.54-.94)	.16	.024	.44	.05

COP: Center of pressure; FQ: Frequency; RMS: Root mean square; EO; Eyes open; EC: Eyes closed; ICC; Intra class correlation coefficient; 95%CI: 95% confidence interval; AP: Anteroposterior; ML: Mediolateral; SEM: Standard error measurement; MDC: Minimal detectable change

## DISCUSSION

The aim of this study was to determine the test-retest reliability of specific frequency bands of postural stability in tandem and single-leg standing tasks in healthy volunteers. Wavelet analysis is used to decompose the center of pressure signal data into several timescale contents, revealing new aspects of postural control mechanisms.

In previous research, the frequency content of COP signals was more often examined in bipedal stances [8,9,12], but in this study, single-leg and tandem stances were tested.

The results of this study that the energy of COP measures with the eyes open had greater values than the eyes closed condition were in line with other studies [8,9]. Our results indicate better reliability of COP energy measures with the eyes closed in the moderate frequency band than the other three frequency band measures for tandem and single-leg stances.

One reason for the high ICC values in the closed-eyes condition that consisted of other studies [16-18] is that because of the deprivation of visual information, postural control maintains the use of visual information within a fixed range, so that the system is not at risk of instability.

In the literature, COP measures are reported in the AP and ML directions because of postural control differences in the sagittal and frontal planes, both from biomechanics and neural control aspects [19].

The RMS of COP signals in the tandem stance except for the very-low-frequency band with the eyes closed and open in the AP direction (ICC=.59, .66, respectively) had ICC values  $\geq$  .78 in the other frequency bandwidths.

Liang et al. (2014) investigated the test-retest reliability

of COP velocity measures in four distinct frequency bandwidths in a bipedal stance condition and demonstrated ICC values  $\geq$  .70 [9]. It seems that ICC values in all COP measures in four frequency bands with the eyes open did not differ significantly for the AP and ML directions. Still, with the eyes closed, COP measures in the ML direction showed greater ICC values than the AP direction.

One potential reason for the significant differences in the COP parameters in the ML axis could be to have a smaller area of the base of support in the ML direction when compared with that in the AP direction. Without vision, the COP sway did not appear to have many excursions in the ML direction to prevent postural instability so that postural control sway could be maintained within a fixed range.

Velocity in the moderate frequency band with the eyes closed in the tandem stance had higher reliability than with the eyes open. In the ML direction, COP velocity measures in the low-frequency band had higher reliability than the AP direction with and without vision.

The results of this study that include high ICC values with closed eyes are consistent with the results of the study by Meshkati et al. (2011) that evaluated COP measures during a double-leg quiet standing condition with the eyes closed and open [17] as well the study by Doyle et al. (2004) that showed better reliability of traditional COP measures with closed eyes than open [7]. Meshkati et al. (2011) reported the reliability of the mean velocity of a double-leg stance on a force plate in athletes with ICCs from 0.45–0.89 [17].

Quek et al. (2014) used wavelet analysis to evaluate postural control. The velocity of COP in frequency bands was

examined and presented as the percentage of the overall COP velocity<sup>8</sup>.

In the research conducted by Bauer et al. (2010), bipedal and Romberg postures were performed, with EO and EC, and the most reliable condition was Romberg with EC. In contrast, the least reliable was bipedal with EO, which is in-line with our observations [20]. In this study, the energy of COP in the low-frequency band for the single-leg stance ( $ICC > .67$ ) was more reliable than the tandem stance ( $ICC > .48$ ). This standing task is more challenging for postural control.

Salavati et al. (2009) reported good reliability of the mean sway velocity in a double-leg stance for a group of healthy controls with their eyes open ( $ICC = 0.91$ ). Clarke et al. (2015) reported an  $ICC = 0.71-0.99$  for sway area in a tandem stance protocol among Canadian Football players [21,22]. According to the results, the energy of COP in the very-low-frequency band with eyes closed in ML direction in the tandem stance ( $ICC > .94$ ) had higher ICC values than the single-leg stance. The ML direction is the smallest base of support. It is perceived as the most challenging direction for single-leg stability despite previous reports of acceptable reliability for ML sway ( $ICC = 0.64-0.65$ ) [23,24]. The tandem stance involves a heel-to-toe position with the toe of the one foot touching the heel of the other, tests lateral postural stability so postural control may hold the extraction of worthwhile vestibular information in a fixed range to prevent postural imbalance.

In the closed eyes condition, the single-leg stance task had higher reliability than the tandem stance, but with the eyes open, the tandem stance had higher ICC values than the other task.

The present study might play a role in postural control assessment, as the reliability of COP measures of signal frequency was examined in tandem and single-leg stance conditions, and time-frequency domain analysis seems to be useful for evaluating postural dynamics in different postural tasks.

## CONCLUSION

Our results reveal that the frequency component of COP signals has moderate-to-excellent test-retest reliability in two standing tasks. These parameters could be of great interest in clinical settings, in the identification of COP dynamics, and methods for the mechanistic exploration of the postural function.

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## Declarations of Interest

None.

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