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Correlation of head and trunk sways, and foot pressure distribution during chewing in the standing position

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Abstract

Purpose: It has been reported that mastication affects the postural control system and enhances postural stability during upright standing. However, the mechanism has not been fully elucidated. The purpose of this study was to verify whether there are correlations among head and trunk sways, and foot pressure distribution during chewing in the standing position. **Methods:** A total of 32 healthy young male subjects were evaluated. The MatScan^{TM} system was used to analyze changes in foot pressure distribution (center of foot pressure: COP) and the three-dimensional motion analysis system was used to analyze changes in head and trunk positions while subjects remained standing position with rest position, centric occlusion, and chewing. Data were analyzed using Spearman's rank correlation coefficients. **Results**: There was a significant positive correlation between trunk sway value and COP areas in all three studied test conditions (correlation 0.75 to 0.95, $P < 0.01$). During mastication, significant positive correlations were also found between head and trunk sway values (correlation 0.70, $P < 0.05$) and between head sway value and COP areas (correlation 0.69 to 0.78, $P < 0.01$). **Conclusions**: There are significant positive correlations among head and trunk sways, and foot pressure distribution during chewing in the standing position.

Keywords: foot pressure distribution; head sway; mastication; standing position; trunk sway

1. Introduction

The proprioceptive information from joint and muscle mechanoreceptors of the neck is integrated with vestibular and visual feedback to control head position, head orientation, and whole body posture [1,2]. In other words, the neck sensory motor system plays an important role in controlling body posture and balance.

It has been reported that there is a functional linkage between jaw and neck regions. Head movements during single and rhythmic jaw opening and closing have also been reported [3,4]. Co-activation of muscles of the jaw and neck-shoulder complex has been shown during mandibular movements and clenching [5,6]. Mastication co-activates jaw and neck muscles leading to coordinated jaw and head-neck movements [7]. These reports indicate the existence of neural connections between the trigeminal and neck sensory and motor systems. In addition, there is also a report supporting a neural linkage between the vestibular and trigeminal systems in humans as indicated by induction or modulation of nystagmus by chewing in patients with Ménière's disease [8]. Based on the above previous reports, it is reasonable to believe that activation of the jaw sensory motor system can modulate the postural control system through its connections to the neck sensory motor system or through its possible direct connections to the vestibular system.

Studies have discussed relationships between masticatory movements, which activate the jaw sensory motor system, and balance of body posture, and have shown that mastication affects the postural control system by enhancing the postural stability during upright standing [9-11]. However, these are the posturography studies that evaluated only the center of gravity sway of standing posture on a force platform, and the mechanism by which mastication enhances postural stability has not been fully elucidated to our knowledge. Furthermore, a recent study [12] has also reported that masticatory movements enhance postural stability during the standing position, but similarly, the mechanism is not yet fully understood to our knowledge.

The head is supported by the trunk via the neck. The height of the body's center of mass is somewhere between 55% (women) and 57% (men) of standing height [13], and the small area of the sole of the foot supports the weight of the whole body. Therefore, stability in head posture is indispensable to the control of body posture during standing position. The head moves in rhythmical coordination with mandibular movements during mastication [7]. Accordingly, as one of the methods to elucidate the mechanism by which mastication enhances postural stability, it would be meaningful and helpful to simultaneously record the head and trunk sways, in addition to the center of gravity sway, and to examine their interrelationships during mastication in the standing position. There are no results to our knowledge from testing of their interrelationship by simultaneously recording the head and trunk sways, and foot pressure distributions during chewing, which are interlocking dynamic movements of the living body.

The purpose of this study was to test the hypothesis in healthy subjects that there are correlations among head and trunk sways, and foot pressure distribution during chewing in the standing position. Toward this goal, the head and trunk sways, and foot pressure distribution during chewing were simultaneously measured and analyzed using motion analyzing and foot pressure distribution measurement system. The findings of this study can be helpful to understand the mechanism by which mastication enhances postural stability, and an interrelationship between stomatognathic function and postural control systems.

2. Material and methods

2.1. Study population and ethics

In total, 32 healthy males with an average age of 26.7 years (range 21-32 years) were included among the students and staff members of the Graduate School of Dental Medicine Hokkaido University. The sample size was calculated using the software program G*Power 3.1.9.2 (Heinrich-Heine-Universität Düsseldorf). When the sample size was calculated by setting α = 0.05, β = 0.8, and effect size = 0.8, 26 participants were needed. All subjects met the following inclusionary criteria: (1) no history of head and neck or back problems, (2) no history of signs and symptoms of temporomandibular disorders or orofacial pain, (3) no history of orthopedic or otolaryngologic problems affecting body balance, (4) absence of prosthesis (i.e., crowns, bridges, implants or removable prosthetics) and class I dental occlusion, and (5) the pattern during mastication is assessed by a linear or concave opening path from centric occlusion toward the working side and a subsequent convex closing path in the vicinity of centric occlusion [14,15]. Exclusionary criteria included: (1) history of head and neck and/or back problems, (2) history of TMD and orofacial pain signs and symptoms, (3) history of orthopedic and/or otolaryngologic problems affecting body balance, (4) presence of five or more permanent dental restorations (i.e., crowns, bridges, implants and/or removable prosthetics), and (5) presence of loose or broken teeth, fillings or crowns which could be further damaged during the course of the study.

The movement of mandibular incisal point during chewing gum on habitual chewing side was recorded by the optical jaw motion tracking device, Motion Visi-Trainer (MVT V1, GC Co., Ltd, Tokyo, Japan) and was analyzed using the overlapping of each cycle and average path [15] (Figure 1).

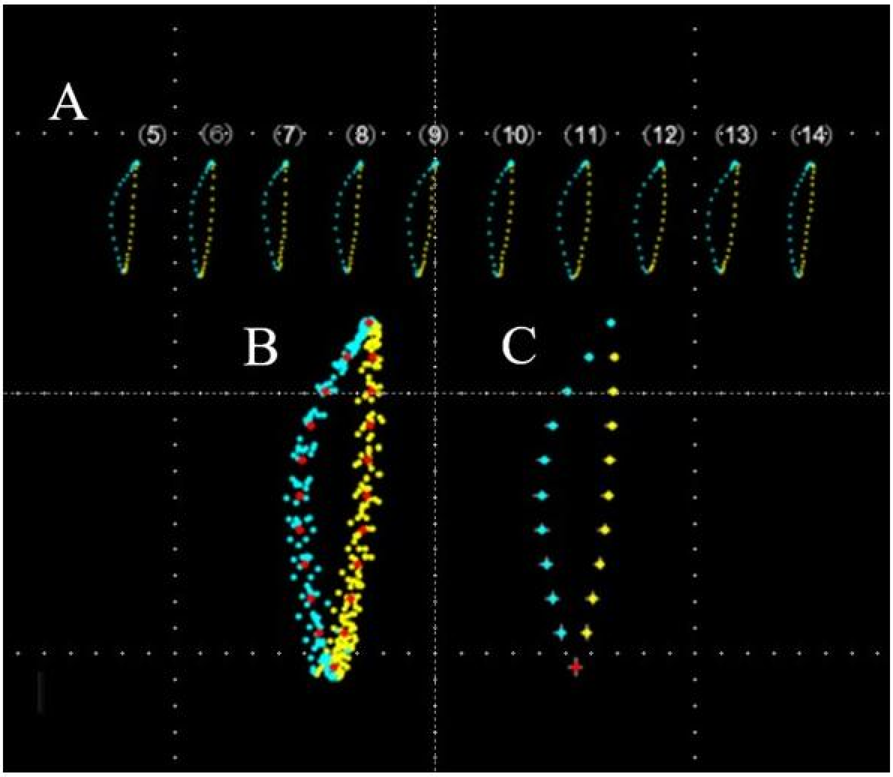


Figure 1. An example of overlapping of cycle and average path during chewing on the right side obtained from one subject. Using the centric occlusion of each cycle as the standard, coordinates for each cycle were determined by vertically dividing the opening and closing paths into 10 equally spaced sections in the frontal view. From these coordinates, the average path and SD (standard deviation) were calculated. The method used to calculate the average path is as follows: (A) 5-14 cycles on the habitual side chewing were recorded, and the coordinates for each cycle were determined by vertical division into 10 equally spaced sections. (B) Overlapping of each cycle and average path. (C) Average path and SDs of each level.

This study was approved by the ethical committee of the Graduate School of Dental Medicine Hokkaido University (2019-No.2). The study methodology was explained, and written consent was obtained from all participants prior to their inclusion in the study.

2.2. Analysis of simultaneous measurements of head and trunk sways, and foot pressure distribution (Figure 2)

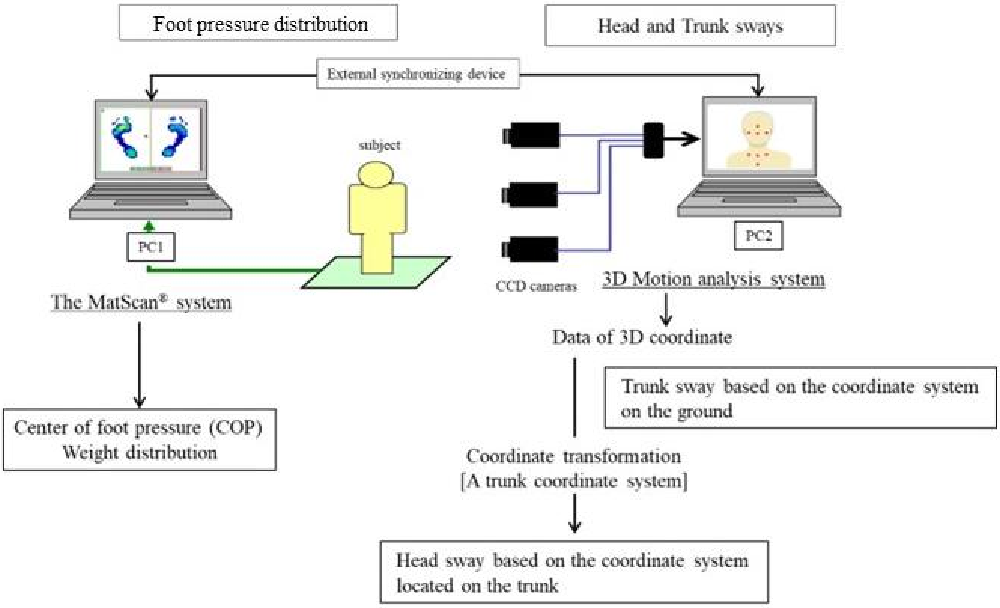


Figure 2. Analysis of simultaneous measurements of head and trunk sways, and foot pressure distribution. Data sampling was performed simultaneously at a sampling rate of 60 Hz using a self-made external synchronization device. For head and trunk sway measurements, a three-dimensional motion analysis system was used to record the motion of target points set on the head and trunk respectively. In the head sway analysis, the coordinates were transformed to a coordinate system, a trunk coordinate system, based on the trunk to eliminate the trunk sway. CCD: Charge coupled device.

The MatScan^{TM} system (Tekscan Inc., Boston, MA, Nitta Corp., Osaka, Japan) was used to analyze foot pressure distribution [12,16-18]. This instrument provided a dynamic evaluation of body posture. This system could measure weight distribution and changes in the position of the COP on a footplate during a standard measuring period. The COP is the center of vertical force acting on the support surface. It indicates gravity shifts in the anteroposterior and lateral directions.

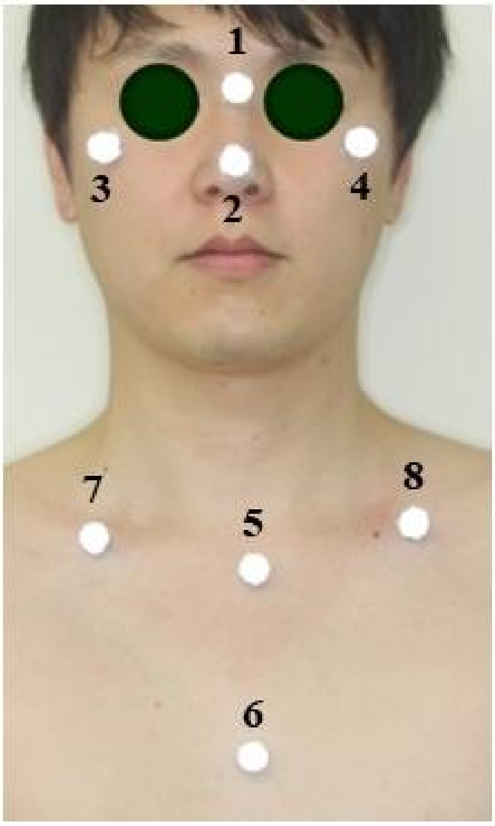


Figure 3. Target points set on the head and trunk. Four target points were set on the head (No. 1-4) and trunk (No. 5-8) respectively for the motion analysis. No. 1: nasion, No. 2: top of the nose, No. 3 and 4: right and left zygomatic bones, No. 5: jugular notch, No. 6: xiphoid process, No. 7 and 8: right and left clavicle middle point. Round reflecting markers (10 mm in diameter) were used as target points to be recognized by using their luminance values, and setting these markers on the head and trunk was used double-sided tape.

The three-dimensional motion analysis system (Library Co., Ltd, Tokyo, Japan) was used to analyze head and trunk sways [12]. This instrument enabled measurement of three-dimensional movements of target points on the surface of the facial skin and body surface simultaneously. The movements of target points were recorded by three charge coupled device (CCD) cameras, and the three-dimensional coordinates were calculated by using analyzing software. Target points on the face and trunk skin were marked by attaching 4 points respectively [12] (Figure 3). The center of 4 target points was calculated in each sampling frame. Then the mean coordinate of all the center of 4 target points on the face was defined as the virtual central coordinate of the head (MCB-h). In the same way, the mean coordinate of all the center of 4 target points on the trunk was defined as the virtual central coordinate of the trunk (MCB-t). The head sway was analyzed based on the coordinate system located on the trunk (A trunk coordinate system). The trunk sway was analyzed based on the coordinate system on the ground [12].

For all tests, subjects were asked to remove their shoes and socks, to stand with their feet apart to the width of their shoulders in a natural stance on the force platform of the MatScan^{TM} system. To assist in obtaining the natural standing posture, the subjects were asked to look directly into a reflected image of their eyes, two meters away with arms hanging free at their sides and to remain in this position during the measurements. Simultaneous measurement of head and trunk sways, and foot pressure distribution was conducted under the following three conditions: (1) The subjects maintained the rest position (teeth slightly apart and masticatory muscles in a relaxed non-contractile condition). (2) The subjects maintained the centric occlusion without clenching. (3) The subjects chew softened chewing gum on their habitual chewing side and were requested not to swallow it for the time tested. These three conditions were randomly conducted in each subject, based on the table of random numbers. Testing under each condition was recorded for 20 seconds. The recording was started after the subject stood on the MatScan^{TM} sensor and the investigator confirmed that their head and body positions were stable. Each trial was recorded three times with a one-minute rest period.

2.3. Parameters

The total trajectory length of the COP (TTL-COP) and COP areas (Rectangular area (RA), Outer peripheral area (OPA), Root mean square area (RMSA)) were used to evaluate the stability of body posture [12,16,18]. For each trial of the MatScan^{TM} system was recorded in 1,200 frames for 20 seconds. The 2-dimensional coordinates of the COP were acquired for every frame. First, the effective distance of the COP between one frame and the next frame was calculated based on the pitch of the sensor sheet in each trial. The TTL-COP for each trial was then calculated by summing up all the effective distances of the COP between 1,200 consecutive frames. The COP areas were the RA, OPA, and RMSA of the total trajectory of 1,200 COPs respectively.

The lateral and anteroposterior weight distribution were used to evaluate balance of body posture [12,16,18]. A four-quadrant weight distribution value was measured in percent (%) for every frame in each trial [12]. First, the lateral weight distribution and the anteroposterior weight distribution values for each frame were calculated. Next, the mean value of the sum of all lateral weight distribution values in each trial was calculated (LWD). The same calculation was carried out for the anteroposterior weight distribution value (AWD). The calculation for the LWD and AWD was as follow: LWD (%) = 50 - (the right-anterior value + the right-posterior value), and AWD (%) = 50 - (the right-posterior value + the left-posterior value) [12]

Head and trunk sway values were used to evaluate the stability of head and trunk positions respectively [12]. For each trial of three-dimensional motion analysis system was recorded in 1,200 frames for 20 seconds. The 3-dimensional coordinate of the center of 4 target points of the head was acquired for every frame. Head sway value (HSV) was defined as the mean distance between MCB-h and each center of 4 target points. The trunk sway value (TSV) was obtained in the same manner as the head sway value [12].

Each trial was repeated three times and the average value of the three trials was used as the representative value for each subject.

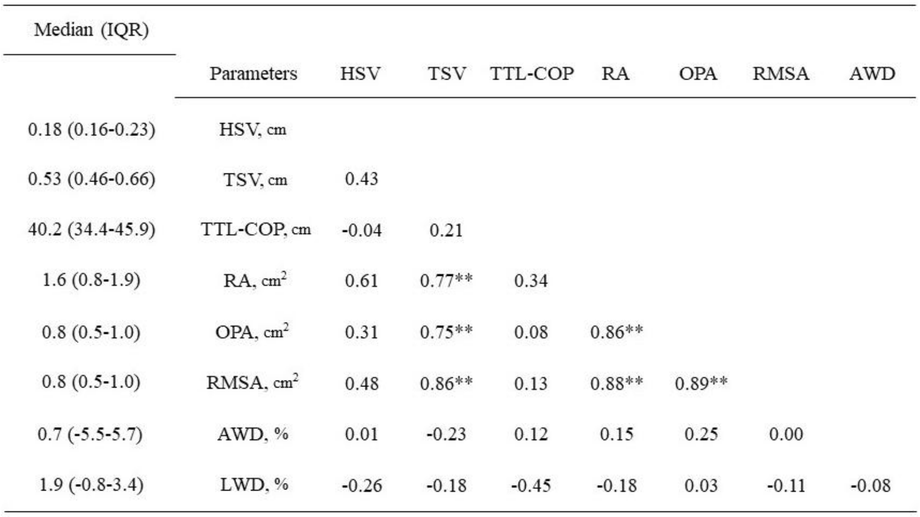
2.4. Statistical analysis

Spearman’s rank correlation coefficient was used to examine the correlation between all parameters to evaluate the interrelationships among head, trunk, and body sways. A P-value < 0.05 was regarded as statistically significant. All statistical analyses were performed in SPSS version 21 (SPSS Japan Inc., Tokyo, Japan).

3. Results

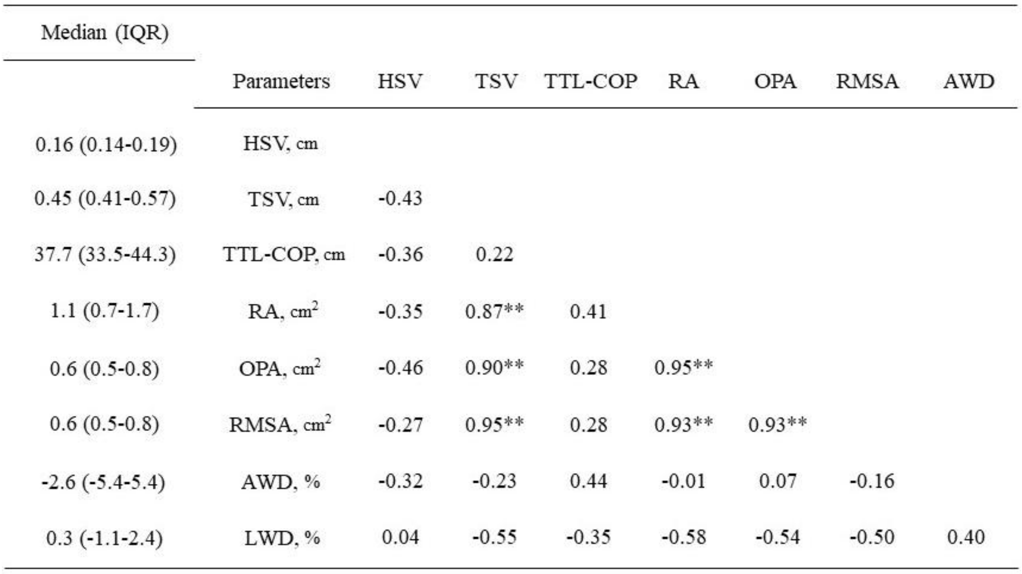
Medians and interquartile range (IQR) for each parameter and all Spearman's rank correlation coefficients between all parameters during rest position are found in Table 1. There was a significant positive high correlation between TSV and COP areas (RA, OPA, RMSA), with a Spearman correlation coefficient 0.75 to 0.86. In addition, COP areas showed a significant positive high association among RA, OPA and RMSA between 0.86 and 0.89.

Table 1. Medians and interquartile range (IQR) for each parameter and Spearman's rank correlation coefficients between all parameters while subjects remained standing position with rest position. Medians (IQR) is shown on the left-hand side and Spearman's rank correlation coefficients on the right-hand side. ** Correlation is significant at the 0.01 level (2-tailed). HSV: Head sway value. TSV: Trunk sway value. TTL-COP: Total trajectory length of the COP. RA: Rectangular area. OPA: Outer peripheral area. RMSA: Root mean square area. AWD: Anteroposterior weight distribution value. LWD: Lateral weight distribution.



Median (IQR)	Parameters	HSV	TSV	TTL-COP	RA	OPA	RMSA	AWD
0.18 (0.16-0.23)	HSV, cm							
0.53 (0.46-0.66)	TSV, cm	0.43						
40.2 (34.4-45.9)	TTL-COP, cm	-0.04	0.21					
1.6 (0.8-1.9)	RA, cm^2	0.61	0.77**	0.34				
0.8 (0.5-1.0)	OPA, cm^2	0.31	0.75**	0.08	0.86**			
0.8 (0.5-1.0)	RMSA, cm^2	0.48	0.86**	0.13	0.88**	0.89**		
0.7 (-5.5-5.7)	AWD, %	0.01	-0.23	0.12	0.15	0.25	0.00	
1.9 (-0.8-3.4)	LWD, %	-0.26	-0.18	-0.45	-0.18	0.03	-0.11	-0.08

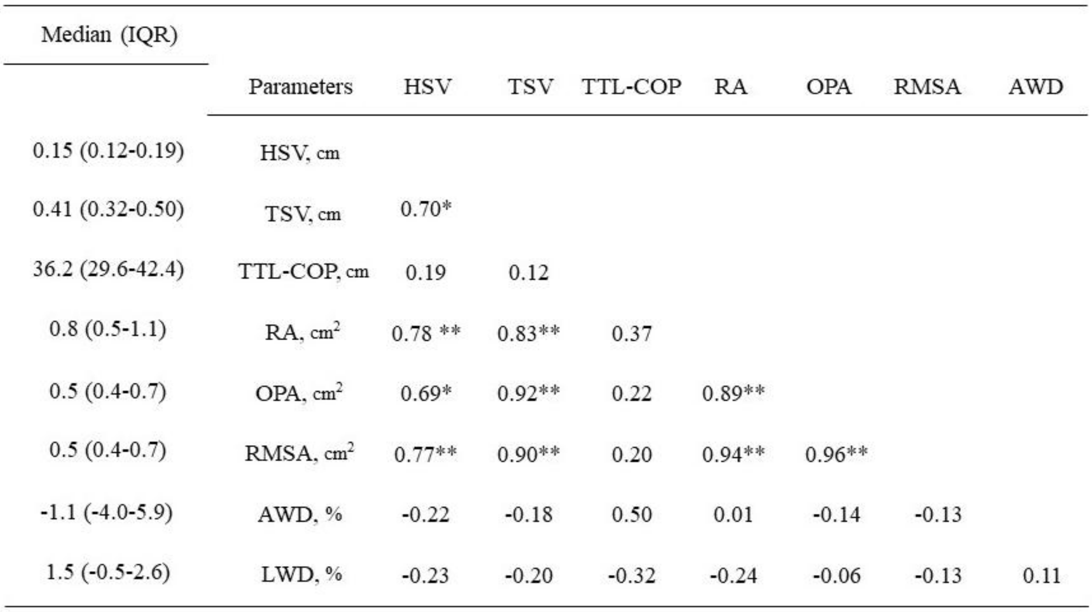
Table 2. Medians and interquartile range (IQR) for each parameter and Spearman's rank correlation coefficients between all parameters while subjects remained standing position with centric occlusion. Medians (IQR) is shown on the left-hand side and Spearman's rank correlation coefficients on the right-hand side. ** Correlation is significant at the 0.01 level (2-tailed). HSV: Head sway value. TSV: Trunk sway value. TTL-COP: Total trajectory length of the COP. RA: Rectangular area. OPA: Outer peripheral area. RMSA: Root mean square area. AWD: Anteroposterior weight distribution value. LWD: Lateral weight distribution.



Median (IQR)	Parameters	HSV	TSV	TTL-COP	RA	OPA	RMSA	AWD
0.16 (0.14-0.19)	HSV, cm							
0.45 (0.41-0.57)	TSV, cm	-0.43						
37.7 (33.5-44.3)	TTL-COP, cm	-0.36	0.22					
1.1 (0.7-1.7)	RA, cm^2	-0.35	0.87**	0.41				
0.6 (0.5-0.8)	OPA, cm^2	-0.46	0.90**	0.28	0.95**			
0.6 (0.5-0.8)	RMSA, cm^2	-0.27	0.95**	0.28	0.93**	0.93**		
-2.6 (-5.4-5.4)	AWD, %	-0.32	-0.23	0.44	-0.01	0.07	-0.16	
0.3 (-1.1-2.4)	LWD, %	0.04	-0.55	-0.35	-0.58	-0.54	-0.50	0.40

Medians (IQR) for each parameter and all Spearman's rank correlation coefficients between all parameters during centric occlusion are shown in Table 2. As during rest position, a significant positive high correlation was observed between TSV and COP areas (RA, OPA, RMSA) 0.87 to 0.95, and COP areas also showed a significant positive high association among RA, OPA and RMSA (correlation more than 0.93).

Table 3. Medians and interquartile range (IQR) for each parameter and Spearman's rank correlation coefficients between all parameters while subjects remained standing position with masticating chewing gum. Medians (IQR) is shown on the left-hand side and Spearman's rank correlation coefficients on the right-hand side. ** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed). HSV: Head sway value. TSV: Trunk sway value. TTL-COP: Total trajectory length of the COP. RA: Rectangular area. OPA: Outer peripheral area. RMSA: Root mean square area. AWD: Anteroposterior weight distribution value. LWD: Lateral weight distribution.



Median (IQR)	Parameters	HSV	TSV	TTL-COP	RA	OPA	RMSA	AWD
0.15 (0.12-0.19)	HSV, cm							
0.41 (0.32-0.50)	TSV, cm	0.70*						
36.2 (29.6-42.4)	TTL-COP, cm	0.19	0.12					
0.8 (0.5-1.1)	RA, cm^2	0.78 **	0.83**	0.37				
0.5 (0.4-0.7)	OPA, cm^2	0.69*	0.92**	0.22	0.89**			
0.5 (0.4-0.7)	RMSA, cm^2	0.77**	0.90**	0.20	0.94**	0.96**		
-1.1 (-4.0-5.9)	AWD, %	-0.22	-0.18	0.50	0.01	-0.14	-0.13	
1.5 (-0.5-2.6)	LWD, %	-0.23	-0.20	-0.32	-0.24	-0.06	-0.13	0.11

Medians (IQR) for each parameter and all Spearman's rank correlation coefficients between all parameters during masticating chewing gum are shown in Table 3. In addition to a significant positive high correlation between TSV and COP areas (RA, OPA, RMSA) (correlation 0.83 to 0.92), significant positive correlations were found between HSV and TSV (correlation 0.70) and between HSV and COP areas (RA, OPA, RMSA) (correlation 0.69 to 0.78). COP areas also showed a significant positive high association among RA, OPA and RMSA between 0.89 and 0.96.

4. Discussion

In the present study, the head and trunk sways, and foot pressure distribution while subjects remained standing position with rest position, centric occlusion, and chewing was simultaneously recorded and examined in healthy subjects to verify whether there are interrelationships among head and trunk sways, and foot pressure distribution during chewing.

Results for Spearman's rank correlation coefficients between TSV and COP areas during rest position, centric occlusion and chewing (Tables 1, 2 and 3) suggested that there was a significant positive correlation between the stability of trunk sway and foot pressure distribution in all three studied test conditions.

The standing posture is the basic posture in which various activities of daily living are initiated. Therefore, the center of mass of the body (COM), which is high [13], must be kept within the narrow base plane consisted of both feet soles to maintain the standing posture [19]. The inverted pendulum model (IP model), in which the COP is the fulcrum and the COM is the pendulum, is often applied to control the standing posture [20-22]. The central nervous system prioritizes postural control to support the body and maintain balance [23], and controls the gap between COM and COP in an anticipatory postural control [24,25]. Mancini et al. [26] developed and validated a practical system that allows to measure postural sway using body-worn accelerometers and found that if the body was thought to be moving like an IP model, a correlation close to 1 would be expected between trunk acceleration and COP displacement during quiet stance.

The present results for the three studied test conditions found that there was a significant positive correlation between TSV and COP areas in the quiet standing position (Tables 1, 2 and 3). Based on the previous reports [19-26] and the concept of an IP model in the control of the standing posture [20-22], the present results suggest that for the stability of static posture, as in quiet standing, the neuromuscular system was governed by intricate postural control mechanisms and constantly worked to maintain the projection of COM within the limits of the base of support, that is, the feet and resulted in a significant positive correlation between trunk sway and COP areas, i.e., body sway in all three studied test conditions. Furthermore, the present results corroborated Mancini’s report [26].

The results for Spearman's rank correlation coefficients between HSV and TSV and between HSV and COP areas during chewing (Table 3) suggested that there were also significant positive correlations between the stability of head and trunk sways and between the stability of head sway and foot pressure distribution during chewing.

The corrective muscular action is required to counter the periodic destabilization in the form of postural sway during standing. It has been reported that chewing induces co-contraction of sternocleidomastoid and trapezius muscles along with jaw muscles [7], the H reflexes in both the pretibial and soleus muscles undergo a nonreciprocal facilitation during mastication [27], and that neck and trunk muscles co-contract with masticatory muscles during jaw clenching [28]. These show the functional integration of the craniocervical region into the neuromuscular system of the body [29] contributing in the feedback control mechanism to control the sway during such dynamic conditions [30].

The present results during chewing found that there were also significant positive correlations between HSV and TSV and between HSV and COP areas during chewing in the quiet standing position (Table 3). Based on the previous reports [7,27-30] and the concept of an IP model in the control of the standing posture [20-22], one can infer that the present results showed the functional integration of the head-neck region (comparable with the mass of an inverse pendulum) into the neuromuscular system of the body contributing in the feedback control mechanism to control the sway during chewing and resulted in significant positive correlations between head and trunk sways and between head sway and foot pressure distribution during chewing. Moreover, the present results found there were significant positive correlations among head and trunk sways, and foot pressure distribution during chewing in the standing position (Table 3). This suggests the possibility that the present results support the body stiffening phenomenon, which was a part of the normal posture control mechanism caused by modification of the fusimotor drive and corresponding enhanced muscle tone [29].

The three COP area variables, RA, OPA and RMSA, were used from the COP trajectory data in this study. The present results showed significant positive correlations among RA, OPA and RMSA in all studied test conditions (Tables 1, 2 and 3). This may have been due to the possibility that the subjects were all healthy subjects met the inclusionary criteria in this study, and therefore, no large transient postural sway was recorded.

Collectively, the results of the present study suggest that there were significant positive correlations among head and trunk sways, and foot pressure during chewing in the standing position. This supports the concept that during dynamic motor task, all subsystems have to be coordinated to enable balanced and stable motor behaviour.

4.1. Limitations

This study has some limitations. The present results showed a correlation among head and trunk sways, and foot pressure distribution during chewing, but their causal relationships could not be determined. It should be necessary to clarify the causal relationships among head, trunk and body sways in order to further deepen understanding of the interrelationships between stomatognathic function and postural control systems. Toward this goal, further approaches for analysis methods are needed in future studies. Furthermore, all subjects in this study had normal masticatory movement path. Therefore, further study should be also needed for subjects with the other patterns of masticatory movement path other than the pattern of masticatory movement path with a linear or concave opening path and a convex closing path.

5. Conclusions

There are significant positive correlations among head and trunk sways, and foot pressure distribution during chewing in the standing position. This has implication for understanding the interrelationship between chewing and posture control system in the standing position.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board at Graduate School of Dental Medicine Hokkaido University, Sapporo, Japan, under reference number 2019-No.2, dated 18 March 2019.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Original data supporting these results are available on reasonable request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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