Chapter

Functional Role of the Somatosensory Information to Perceive the Standing Position in the Anteroposterior Direction

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Abstract

The perceptibility of standing positions in the anteroposterior direction varies according to the standing position. Standing positions with the center of foot pressure (COP) located far from the COP in the quiet standing position show lower stability, and the perceptibility was markedly higher in comparison to positions with the COP near the COP in the quiet standing position. This chapter focuses on the role of somatosensory information in the perception of standing positions in the anteroposterior direction based on our previous study, which concluded that a large change in sensory information generated from the sole of the heel and knee may provide important cues regarding the perception of standing positions with low stability. Large changes in the somatosensory information generated from pressure changes on the sole and from the upward movement of the patella leaning forward or backward while standing may contribute to the position information.

Keywords: somatosensory information, perception, standing positions, anteroposterior direction

1. Introduction

The control of the standing posture in humans requires various sensory systems, including visual [1], vestibular [2, 3], plantar sole mechanoreceptor [4–8], and proprioceptive [9] systems. The central nervous system (CNS) integrates these different sensory inputs. Upright posture control was performed in various standing positions on the anteroposterior and mediolateral directions. When both arms are rapidly flexed to the front from the quiet standing (QS) posture, the postural muscles (the erector spinae, hamstrings, etc.) are activated 20–30 ms earlier than the focal muscles of the upper extremities (the anterior deltoid) [10]. This earlier activation of the postural muscles in comparison to the focal muscles was defined as the anticipatory postural control to minimize the effect of forthcoming body perturbations due to arm movement [11]. This anticipatory activation of the postural muscles during the QS position was significantly slower than that in the standing position near the most forward-leaning position [10]. Thus, because the preceding time of the earlier activation of the postural muscles varies according to the initial standing position just before arm movement, the initial standing position may be accurately perceived.

Schiffman described that "Perceptions are associated with the organization and integration of sensory attributes, that is, the awareness of 'things' and 'events' rather than mere attributes or qualities" [12]. Thus, the standing position may be perceived in association with things and events falling and stability. The proprioceptive sensory information concerned with postural control is processed through two routes (cognitive processing and sensorimotor processing) in the CNS [13]. Cognitive processing acts on the perception of the body position [13]. On the other hand, sensorimotor processing regulates the posture via reflex and automatic loops [13]. A previous study reported that the stability of standing posture is higher when the center of the foot pressure in the foot is located 30–60% from the heel to the length of the foot in the anteroposterior direction [14]. When the center of foot pressure deviates from this range, the stability of standing posture largely decreases [14]. Sensorimotor processing may act strongly in a stable standing position (30–60% from the heel to the length of the foot), while cognitive processing may operate strongly in an unstable standing position (deviating from this range) in order to maintain safety. It was reported that the perception of the standing position in the anteroposterior direction was accurate in the unstable position [15].

The role of somatosensory information in the perception of standing positions in anteroposterior direction is discussed in this chapter based on our previous studies' findings as follows: (1) the large changes in the plural sensory information from the sole when the center of the foot pressure is located approximately at 70% of the foot length mutually play an important role in perceiving the standing position; (2) the perception of pressure information at the head of the first metatarsalis reaching a maximum is related strongly to that of pressure information in first toe; (3) in cases in which the patella moves while leaning backward, the patellar movement is accurately perceived; and (4) the large changes in the sensory information that are induced by patellar movement are a cue for the perception of the standing position while leaning backward.

2. Somatosensory information from the plantar sole when leaning forward while standing

2.1 The distribution of foot pressure when the body leans forward and perception of large changes of foot pressure

The distribution of foot pressure when the body leans slowly forward was reported [4]. When slowly leaning forward from the quiet standing position to the most forward-leaning position, the position at which the pressure at the head of the first metatarsalis showed the maximum value was 71.0% of the foot length, and the perceived position of this maximum value was 70.5% of the foot length (**Table 1**) [4]. There was no significant difference between the two positions. A significant correlation (r = 0.86; t = 4.99) was found between both positions [4]. Thus, this maximum pressure was correctly perceived.

The first toe pressure increased in two forward-leaning standing positions with the subject leaning forward from the quiet standing position. The first pressure increasing position was 60.9% of the foot length, the second was 69.5% of the foot length, and the perceived position of the second position was 70.9% of the foot length [4]. None of the subjects were able to perceive the first large increase in the first toe pressure. A significant correlation (r = 0.92; t = 7.23) was found between the position of the center of pressure in the foot at the second large increase and the perceived position (**Table 1**) [4]. The second increase of the first toe pressure was correctly perceived as well as that of the first metatarsalis maximum pressure.

	Pressure at head of first metatarsalis		Pressure at first toe	
	Maximum pressure	**Perception**	**Second large increase**	**Perception**
Position	71.0 ± 3.1	70.5 ± 3.7	69.5 ± 2.6	70.9 ± 3.2
Correlation	r = 0.86* (t = 4.99)		r = 0.92* (t = 7.23)	

**Significant correlation between the position of maximum pressure at the head of first toe and its perceived position, and between the second large increase position of the first toe and its perceived position.*

Table 1.
Positions of center of foot pressure (% of foot length: %FL) and correlation: maximum pressure at head of first metatarsalis and second large changes in pressure at first toe (modified from [4]).

Since the standing positions where the first large increase in pressure at the first toe took place when standing were very steady, the probability that the information of this large increase was processed via a sensorimotor processing route is high. The standing position at the second large increase of the first toe was 70% of the foot length, which was well out of the very steady positional range (30–60% from the heel to the length of the foot), the probability that the information of this large increase was processed via a cognitive processing route is high.

It is noteworthy that the standing position at the maximum pressure at the first metatarsalis (approximately 70% of the foot length) is similar to the position of the second large increase in pressure at the first toe, and the correlation between both positions and between both perceived positions was high [4]. At approximately 70% of the foot length, the foot pressure shifted from the heads of the metatarsalis to the toes on the boundary of this position. The most forward-leaning position is 83% of the foot length [4]. Approximately 10% of the foot length is the difference between the standing position at the maximum pressure at the first metatarsalis and the most forward-leaning position. This difference represents an important safety margin when maintaining forward-leaning standing. Thus, the large changes in the plural sensory information from these areas at approximately 70% of the foot length mutually play an important role in perceiving the standing position through the cognitive processing route [4].

2.2 Influence of cooling of the sole on the perception of large changes in foot pressure

To investigate the relationship of the pressure sensation between the first toe and the heads of the metatarsalis, these areas were cooled [4]. A cooling device set at 1°C was used to reduce the sensitivity of the first toe or the head of the first metatarsalis. To continue cooling these regions during the measurement period, an iron plate cooled to 1°C was placed flush with the floor of the force plate and was changed on every trial (**Figure 1**) [4].

All subjects (n = 11) could perceive the maximum pressure at the head of the first metatarsalis, as described above. When the head of the first metatarsalis was cooled, 8 of 11 subjects could perceive the maximum pressure at the head of the first metatarsalis. When the first toe was cooled, 10 of 11 subjects could perceive the maximum pressure at the head of the first metatarsalis. There were no statistically significant differences among the three conditions (**Table 2**) [4]. Thus, cooling of the head of the first metatarsalis or the first toe had no effect on the perception of the maximum pressure at the head of the first metatarsalis.

On the other hand, all subjects could perceive the second large increase in first toe pressure, as described above. When the head of the first metatarsalis was

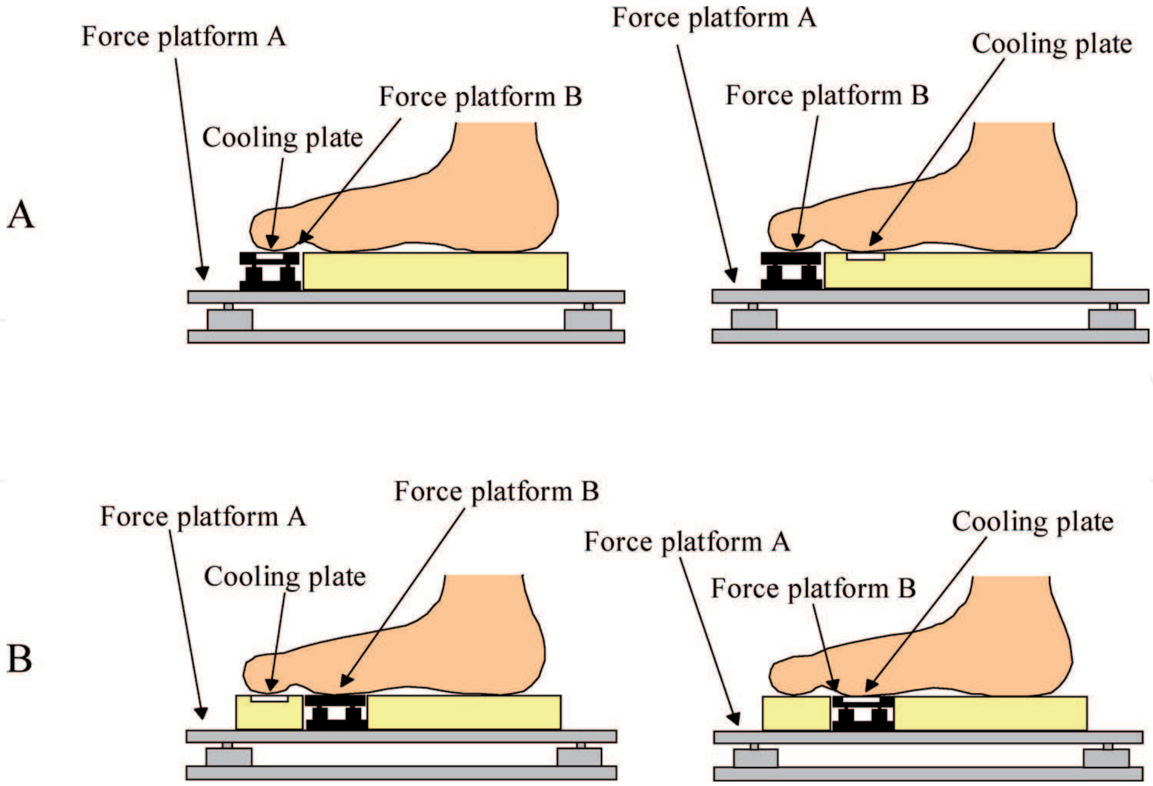

Figure 1.
Diagrams of apparatus. (A) Measuring pressure at the first toe under the cooling condition of the first toe (left panel) and under the cooling condition of the first metatarsalis (right panel). (B) Measuring pressure at the head of the first metatarsalis under the cooling condition of the first toe (left panel) and under the cooling condition of the first metetersalis (right panel) (modified from [4]).

Condition		Pressure at head of first metatarsalis	Second large increase at first toe
Normal (non-cooling)		11	11
Cooling	Head of first metatarsalis	8	6*
	First toe	9	9

**Significantly different from the normal condition.*

Table 2.
Number of subjects who could perceive the maximum pressure at the head of first metatarsalis, second large increase in first toe pressure under normal and cooling conditions (modified from [4]).

cooled, 6 of 11 subjects could perceive the second large increase in first toe pressure (**Table 2**) [4]. Thus, cooling the head of the first metatarsalis significantly affected the perception of the second large increase in first toe pressure. When the first toe was cooled, 9 of 11 subjects could perceive the second large increase in first toe pressure (**Table 2**) [4]. This result suggested that cooling the first toe did not significantly affect the perception of the second large increase at the first toe.

These experiments performed under cooling conditions demonstrated the following: (1) subjects could perceive the maximum pressure at the first metatarsalis when the first metatarsalis was cooled; (2) subjects could perceive the second large increase in first toe pressure when the first toe was cooled, whereas they could not perceive this when the first metatarsalis was cooled. The results suggested that the pressure information at the head of the first metatarsalis reaching a maximum is related strongly to the second large increase of pressure information in first toe. Based on this relationship, the second large increase in pressure at the first toe and the maximum pressure at the head of the first metatarsalis are perceived at approximately the same time in the same standing position. In addition, the pressure information at the head of the first metatarsalis may have greater priority in the perception of the second large increase in pressure at the first toe [4].

3. The upward movement of the patella while leaning backward may contribute to the position information

3.1 Perception of upward patellar movement in the backward-leaning standing position

While gradually leaning backward from the quiet standing position, a large increase of activity in the rectus femoris is typically observed at approximately 30–35% of the foot length [4]. However, most participants are unable to perceive this large increase [4]. The patella is a sesamoid bone that is connected to the quadriceps tendon, and the knee joint capsule surrounding the patella also adheres to the patella tendon [16, 17]. Thus, the upward movement of patella may cause deformity of the knee joint capsule and the cutaneous tissues surrounding the knee. Edin reported that sensory information from cutaneous receptors in the anterior thigh close to the knee joint plays an important role in the perception of the knee joint position [18]. The large changes in the somatosensory information produced by the patellar movement should contribute to the perception of a specific backward-leaning standing position. It is considered that participants whose patella moves clearly during backward-leaning standing also clearly perceive large changes in the somatosensory information associated with patellar movement.

Twelve young adult subjects maintained the quiet standing posture for 3 seconds and then slowly moved from their initial standing position to the most backward-leaning standing position over approximately 10 seconds [19]. The experiment was conducted under two conditions. In condition 1, the quadriceps femoris was relaxed (relaxed-start condition). In condition 2, the quadriceps femoris was contracted raising the patella superiorly (contracted-start condition). Four trials were performed under each condition. To analyze the patella range of motion, X-ray exposure was performed under the relaxed-start condition [19].

Under the relaxed-start condition, patellar movement while leaning backward was confirmed in all 4 trials for 8 of the 12 subjects; 3 subjects showed no patellar movement in all 4 trials. Patellar movement was confirmed in 35 of the 48 trials; the mean patellar range of motion in these trials was 9.5 mm (SD = 3.0 mm) (**Figure 2**) [19]. However, two trials in which patellar range of motion was <3.5 mm (9.5 mm—2SD) were classified as non-movement trials. Thus, 33 trials were patellar movement trials and 15 were patellar non-movement trials (**Table 3**) [19]. In the patellar movement trials, 30 trials were perceived and 3 trials were not perceived; thus, 90.9% of these trials were perceived. On the other hand, 66.7% of the trials were perceived in the non-movement trials. There was a significant difference between the two rates (**Table 3**) [19].

Under the contracted-start condition, 37 trials were perceived and 11 trials were not perceived. The rate of the perceived trials under the contracted-start condition was 77.0%. This rate was significantly smaller in comparison to the patellar movement trials performed under the relaxed-start condition (**Table 3**) [19].

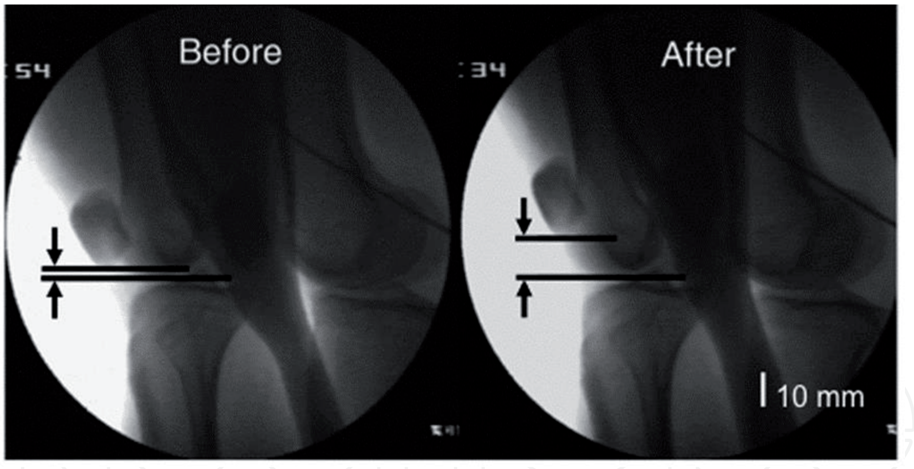

Figure 2.
Typical X-ray photographic image of the patellar movement. Left side: before movement, right side: after movement ([19]).

	The relaxed-start condition		The contracted-start condition
	Patellar movement trials	Patellar non-movement trials	
Total trials	33	15	48
Perceived trials	30	10	37
Not perceived trials	3	5	11
Rate of perceived trials (%)	90.9*	66.7	77.0

**There was a significant difference between patellar movement trials and patella non-movement trials under the relaxed-start condition.*

Table 3.
Results of perceptibility of patellar movement in the relaxed-start and the contracted-start conditions (modified from [19]).

Patellar movement in all four trials in the relaxed-start condition was confirmed in eight participants. In contrast, three participants did not show patellar movement in any of the four trials. Thus, there were participants whose patella moved and those whose patella did not move when the subjects were leaning backward. In the patellar non-movement trials, slight flexion of the knees or contraction of the rectus femoris muscle was observed while the participants were in the quiet standing position [19].

The rate of perceived trials under the relaxed-start condition was significantly higher than that of the patellar non-movement trials under the same condition. Conversely, the rate of perceived trials in the patellar non-movement trials under the relaxed-start condition did not differ from that under the contracted-start condition. The contracted-start condition may simulate the patellar non-movement trials under the relaxed-start condition [19].

Mechanoreceptors within the muscles, joint capsules, ligaments, and skin supply information about the joint position and movement contributing to positional perception [18, 20–24]. Thus, in cases in which the patella moves while leaning backward, the patellar movement is accurately perceived through large changes in the sensory information obtained via mechanoreceptors within the muscles, joint capsules, ligaments, and skin around the patella. Consequently, the large changes in the sensory information that are induced by patellar movement are a cue for the perception of the standing position while leaning backward.

3.2 Perception of the position when leaning backward while standing and during patellar movement

The rectus femoris muscle is significantly activated in the standing position when gradually leaning backward from the quiet standing position and that position is almost constant in each individual [4]. Thus, large changes in somatosensory information based on patellar movement while leaning backward may contribute to the perception of a specific backward-leaning standing position. The perceptibility of the standing position is particularly high near the position of patellar movement, where the large change in sensory information is perceived [25]. Investigating the function of the sensory information based on patellar movement in the perception of backward-leaning standing position is important for understanding the mechanism through which stability is maintained during backward-leaning and through which prevents the individual from falling backward.

Fourteen healthy young adults (six women and eight men) were selected according to three criteria: (1) relaxed quadriceps femoris in the quiet standing position; (2) free movement of patella on palpation in the quiet standing position; and (3) the presence of upward patellar movement while leaning backward. In the experiment, the onset of patellar movement was confirmed using an acceleration waveform generated by an accelerometer taped to the upper edge of the patella [25].

Ten trials were conducted to identify the onset position of patellar movement while leaning backward from the quiet standing position. The onset position of the patellar movement was 35.1 ± 4.5% of the foot length. The individual mean value of the standard deviation for the onset position was very small (2.5 ± 1.3% of the foot length) [25].

The perceptibility of three reference positions was evaluated from the reproducibility of these positions, which was determined according to the absolute error between the reference position and the reproduced position. The reference positions set for each participant were as follows: the COP position at the patellar movement onset position (the onset position), +5% foot length from the onset position, and − 5% foot length from the onset position. The mean of +5% foot length from the onset position was 40% of the foot length and that of −5% foot length from the onset position was 30% of the foot length [25]. The mean absolute error at both the +5% foot length and the −5% foot length from the onset position was defined as the expected value. The ratio of the absolute error in the onset position to the expected value was calculated as the perception error index. A smaller absolute error and smaller perception error index reflect higher perceptibility [25]. The absolute error at +5% foot length from the onset position, the onset position, and − 5% foot length from the onset position were 4.9 ± 2.00% of the foot length, 1.9 ± 0.51% of the foot length, and 2.7 ± 0.90% of the foot length, respectively (**Table 4**). The reference position was found to have a significant effect on the absolute error ($p < 0.001$). The absolute error values at the onset position and −5% foot length from the onset position were significantly smaller in comparison to that at +5% foot length from the onset position. The perception error index was 54.1 ± 18.5%, and this value was significantly smaller than the expected value ($p < 0.001$) (**Figure 3**) [25].

Patellar movement was accurately perceived while moving the patella [19]. In this study, the mean standard deviation of the patellar moving onset position was small. Hence, because the onset position is located at a constant position in each

	Reference positions		
	The −5% of foot length from the onset position	**The onset position**	**The +5% of foot length from the onset position**
Absolute error (%FL)	2.7 ± 0.90	1.9 ± 0.51*	4.9 ± 2.00
The perception error index (%)		54.1 ± 18.51**	

**Statistically smaller than the +5%FL from the onset position.*
***Statistically smaller than the expected value (100%).*

Table 4.
Absolute error in three reference positions and the perception error index in the onset position (modified from [25]).

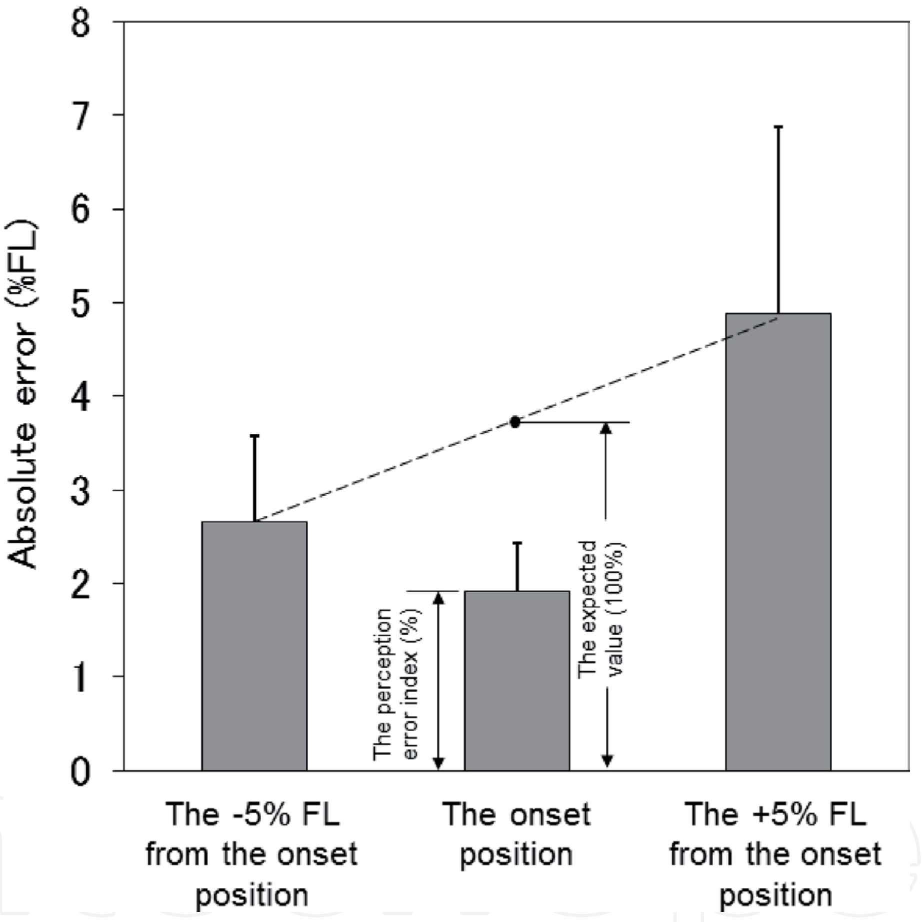

Figure 3.
Absolute error of the three reference positions, and the calculation method for perception error index ([25]).

participant, the large change of sensory information should play an important role in the individual's postural stability at the onset position. It is considered that the standing position is accurately perceived by building up the sensory reference frame based on the large change of sensory information caused by the patellar movement [25]. The onset position (approximately 35% of the foot length) is located near the posterior end of the stability range for the standing position. As a result, the absolute error in the onset position was significantly smaller than that at +5% of the foot length from the onset position. In addition, the absolute error in the onset position was same as that in position about 25% of the foot length. The heel pressure distribution was reported to change substantially approximately near 25% of the foot length and the perceptibility of this change was highly accurate [26]. Since stability of the standing posture reduces posteriorly to the end of this range [27], the large increase in sensory information associated with patellar movement when leaning backward while standing may represent warning information [25].

3.3 Relevance and application to physical therapy

In this chapter, the role of the somatosensory information in the perception of the standing positions in the anteroposterior direction is discussed based on the findings of our previous study.

During forward-leaning standing, the large changes of somatosensory information from the metatarsalis and the toes may have an important role in the perception of the standing position. The relationship between the pressure information of the first toe and the first metatarsalis is particularly strong to perceive the standing position at approximately 70% of the foot length. During backward-leaning standing, the large changes in somatosensory information associated with the onset of patellar movement may have an important role in the perception of the standing position at the posterior end of the stability range for the standing position.

The somatosensory information for the perception of the body position for motor control is important for physical therapy. Thus, physical therapists should consider which sensory information is weighted and which sensory information is re-weighted by CNS to perceive the body position on the reference frame for balance control in patients.

4. Conclusion

This chapter showed and discussed the important role of the somatosensory information from the sole and around the patella to perceive the standing position in anteroposterior direction. During forward-leaning standing, the large changes in the pressure information at the head of the first metatarsalis and the first toe at approximately 70% of the foot length mutually play an important role in perceiving the standing position. The perception of pressure information at the head of the first metatarsalis reaching a maximum is strongly related to that of pressure information in first toe. In cases in which the patella moves while gradually leaning backward from the quiet standing position, the upward movement of patella may cause deformity of the knee joint capsule and the cutaneous tissues surrounding the knee. The mean standard deviation of the patellar moving onset position was small. Hence, because the onset position is located at a constant position in each participant, the large changes in the sensory information induced by patellar movement are a cue for the perception of the standing position while leaning backward.

Conflicts of interest

The author has no conflicts of interest directly relevant to the content of this chapter.

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