Motor Control, **(Ahead of Print)**
https://doi.org/10.1123/mc.2018-0119

Human Kinetics
ARTICLE

Sensory Reweighting During Bipedal Quiet Standing in Adolescents

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A cross-sectional, prospective, between-subjects design was used in this study to establish the differences in sensory reweighting of postural control among different ages during adolescence. A total of 153 adolescents (five age groups; 13–17 years old) performed bipedal standing in three sensory conditions (i.e., with visual restriction, vestibular disturbance, and proprioceptive disturbance). Center of pressure displacement signals were measured in mediolateral and anteroposterior directions to characterize reweighting in the sensory system in static postural control when sensory information is disturbed or restricted during adolescent growth. The results indicate a development of postural control, showing large differences between subjects of 13–14 years old and older adolescents. A critical change was found in sensory reweighting during bipedal stance with disturbance of proprioceptive information at 15 years old. Adolescents of 13–14 years old showed less postural control and performance than older adolescents during the disturbance of proprioceptive information. Moreover, the results demonstrated that the visual system achieves its development around 15–16 years old. In conclusion, this research suggests that a difference of sensory reweighting under this type of sensorial condition and sensory reweight systems would seem to achieve stabilization at the age of 15.

Keywords: adolescence, motor learning, postural stability, sensory disturbance

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Maintaining standing balance is characterized by small and continuous adaptations around the vertical axis to preserve stability. For the conservation of body stability, the coordinated integration of information from different sensory systems involved in postural control is required (i.e., visual, the vestibular and the proprioceptive, and plantar cutaneous information). Using this information, the central nervous system sends appropriate stimuli to the muscles involved in postural control, which are mainly used to move the hip, knee, and ankle (Nashner, 1993).

Several conceptual models have been used to characterize multisensory integration in postural control and spatial orientation (Jeka, Oie, & Kiemel, 2000; Mahboobin, Loughlin, Redfern, & Sparto, 2005; Oie, Kiemel, & Jeka, 2002; Peterka & Loughlin, 2004; van der Kooij, Jacobs, Koopman, & van der Helm, 2001). Some authors have suggested that the integration of information from these sensory systems appears to be dynamically regulated to adapt to the changing environmental conditions and the sensory information available, a process sometimes called sensory reweighting (Mahboobin et al., 2005; Oie et al., 2002; Peterka & Loughlin, 2004; van der Kooij et al., 2001). The integration of information involves the central nervous system detecting and weighting the sensory information received from the different systems, providing the most reliable and useful landscape to maintain balance. A key concept of this model is the weight of the sensory systems, which describes the preponderance of each system's information to maintain balance (Mahboobin et al., 2008). For example, in the bipedal position, with eyes closed, on a stable surface, the primary sensory source of information on body orientation in space is provided by the somatosensory system. When the condition changes by moving the platform, the primary source of sensory information changes to vestibular. This fact contributes to the variation of sensory systems to maintain body stability in environmental conditions.

To study the contribution of different sensory systems to postural regulation, sensory manipulations have been commonly used. The disturbance or restriction of one or several sensory systems impacts the contribution of the rest of the systems.

For example, when normal vision is altered or restricted, body sway tends to increase (Lee & Aronson, 1974). Another environmental condition that could affect postural stability is sound. Although the number of studies published in this field is limited, some findings suggest that sound influences the vestibular system because of its relationship with the organs of Corti (in the inner ear) and the eighth cranial nerve, which is responsible for transmitting neural impulses related to vestibular and hearing systems (Bordoni & Daly, 2019). Furthermore, as the vestibular fluid environment is shared by the auditory end organ and vestibular system, they are also affected by intense acoustic waves. Golz et al. (2001) observed that intense sounds caused disturbances in the vestibular system. Finally, proprioceptive disturbance has been mainly studied by manipulating the myotatic and tendon sensors. Tendon vibration is one of the most used techniques to disrupt the myotendinous complex, which results in the modification of the orientation of the body (Ceyte et al., 2007; Thompson, Bélanger, & Fung, 2007).

The reliance attributed to the sensory systems in the context of sensory-manipulated conditions also varies with age (e.g., children or adolescents; Polastri & Barela, 2013). Children largely depend on the visual system to maintain body stability (Lee & Aronson, 1974; Lishman & Lee, 1973). This preponderance is reduced progressively as the proprioceptive system is developed during childhood and adolescence (Barela, Barela, Rinaldi, & de Toledo, 2009; Godoi & Barela, 2008). Indeed, different studies (Lee & Aronson, 1974; Lishman & Lee, 1973; Riach & Hayes, 1987; Rival, Ceyte, & Olivier, 2005; Woollacott, Debu, & Mowatt, 1987) have suggested that children aged less than 7 years are not able to properly integrate sensory information from the different systems. Thus, postural control is mainly based on visual information (even after the first decade of life) because of the fact that children do not mainly use somatosensory cues to stabilize posture (Godoi & Barela, 2008; Peterson, Christou, & Rosengren, 2006; Sparto et al., 2006). Nevertheless, Polastri and Barela (2013) found similar sensory reweighting capacities in 12-year-old children as in young adults when visual information was manipulated. These results suggest that the development of the involvement of sensory systems in postural control is completed by early adolescence.

Unfortunately, the change that occurs in the sensory systems responsible for maintaining postural control in quiet standing from early adolescence to young adult has not been studied in detail. Knowledge on the development of sensory reweighting capability during adolescence in conditions in which visual, vestibular, proprioceptive, and cutaneous sensory information are changing is lacking. Thus, the aim of this study was to study the involvement of postural control and the reweight function in the bipedal standing position in the development of each sensory system when the sensorial information is manipulated or restricted in adolescents.

Methods

Participants

A cross-sectional, prospective, between-subjects design was used to establish the differences in sensory reweighting in adolescents of different ages. Using a nonprobability sampling method, 153 adolescents from 13 to 17 years of age were chosen to participate in the study and divided into five age groups. The inclusion criteria were (a) between 13 and 17 years of age (both inclusive) and (b) the absence of any motor control pathology. The characteristics of the subjects in the groups are presented in Table 1.

Previous approval was obtained from the institutional review board of the University of Valencia. The protocols used in the study met all the requirements set out in the 1964 Declaration of Helsinki and in the later revisions. All the adolescents participated voluntarily in this study, with the signed consent of their parents.

Procedure

Center of pressure (COP) signals were acquired from a Wii Balance Board. This device has been validated as a good means of analyzing postural control in the standing position in a number of studies in both adults (Clark et al., 2010; Park & Lee, 2014) and children (Larsen, Jørgensen, Junge, Juul-Kristensen, & Wedderkopp, 2014). Raw data were acquired using the WiiLab software

Table 1 Participants' Characteristics

Variable	13 years old ($n = 30$)	14 years old ($n = 30$)	15 years old ($n = 31$)	16 years old ($n = 31$)	17 years old ($n = 31$)
Sex					
Boys	15	15	15	15	16
Girls	15	15	16	16	15
Weight (kg)	58.11 (2.26)	59.55 (2.27)	61.69 (1.98)	62.40 (1.87)	62.44 (3.15)
Height (cm)	161.50 (1.36)	165.10 (1.66)	168.79 (1.88)	168.00 (1.55)	165.00 (5.83)
BMI (kg/m^2)	22.09 (0.62)	21.67 (0.51)	21.53 (0.46)	22.01 (0.46)	22.06 (0.57)
BMI (percentile)	75.15 (3.68)	69.37 (3.55)	62.90 (4.14)	61.72 (3.84)	50.90 (4.78)

Note. Data are expressed as mean (SEM) except for sex in which the number of boys and girls in each group is reported. BMI = body mass index.

(University of Colorado Boulder, Boulder, CO) for MATLAB R2015 (MathWorks Inc., Natick, MA). The Wii Balance Board was placed on a stable surface on the floor. Data signals were recorded at a frequency of 40 Hz.

All the adolescents were assessed in the school they attended. During the measurements, the adolescents had to remain barefoot, in the bipedal position, as quiet as possible, and with arms relaxed for 50 s. This position was repeated in three different conditions. Their feet were parallel and separated by a distance equal to their shoulder width. A supervisor checked that the same position was used in each trial. The total duration of each condition was divided into three blocks without rests in between. The order of the conditions was randomized among the subjects. A detailed description of the sensory disturbance/restriction is provided below, and these tests have been used based on the study of Paillard and Noé (2015).

(a) Quiet standing condition with visual restriction: The first block of the test, standing with eyes open, had a duration of 20 s. In the second block, the eyes were closed for 15 s. Finally, the eyes were open for the last 15 s of the test (i.e., Block 3).

(b) Quiet standing condition with vestibular disturbance: The first block of the test had a duration of 20 s, standing with eyes open and without any noise. In the second block, the subject listened to white noise through headphones at an intensity of 90 dB. In the last 15 s of the test, there was no noise (i.e., Block 3).

(c) Quiet standing condition with manipulation of proprioception disturbance: The first block of the test lasted 20 s, with the subjects standing and their eyes open. In the second block, two custom vibrators with unbalanced masses installed at both extremities of a direct current motor were created. Each motor was embedded in a plastic cylinder of 10 cm long and 3 cm in diameter, which produced a mechanical vibration (85 Hz and an amplitude of

1 mm), and was applied to both Achilles tendons (Billot, Handrigan, Simoneau, & Teasdale, 2015). In the last 15 s of the test, no vibration was applied (i.e., Block 3).

Data Analysis

Center of pressure displacement signals in the mediolateral (ML) and anteroposterior (AP) directions were dual pass, filtered by a Butterworth low-pass filter with a 12-Hz cutoff frequency. As delayed stabilization had previously been reported (Raymakers, Samson, & Verhaar, 2005), the first 5 s of each trial were excluded from the analysis. The signals were then segmented into three 15-s blocks (i.e., no sensory disturbance/restriction, sensory disturbance/restriction, and restoring initial conditions). For each block, the mean velocity in the anteroposterior (MV_{AP}) and mediolateral directions (MV_{ML}) and the 95% confidence interval ellipse area (EA) were calculated using equations proposed by Prieto, Myklebust, Hoffmann, Lovett, and Myklebust (1996). The EA indicates the size of the area generated by the displacement of the COP on the platform during the trial. It is an index of overall postural performance (Paillard & Noé, 2015). MV, which reflects neuromuscular activity, is required to maintain the bipedal standing position (Paillard & Noé, 2015).

Statistical Analysis

The SPSS software (version 21; SPSS Inc., Chicago, IL) was used for the statistical analysis. The Kolmogorov–Smirnov test was used to analyze the variables' distribution. Standard statistical methods were used to obtain the mean as a measure of the central trend and the *SD* as a measure of dispersion. For each balance condition, a mixed-model multivariate analysis of variance (Groups [five ages] × Block [three conditions]) was applied to establish the effects of group and sensory disturbance/restriction on the dependent variables. The follow-up to the multivariate contrast was performed by univariate contrast to determine the effect of age and block in the dependent variables (i.e., EA and mean velocity in AP and ML directions). Partial eta squared was used as the effect size of the multivariate and univariate contrasts. When the univariate contrasts showed statistically significant main or interaction effects, pairwise comparisons were performed using the Bonferroni correction. This correction was applied in all results. A *p* value of .05 was accepted as the level of significance for all statistical analyses.

Results

Restriction of the Visual Information

The main effects of the block, $F(6, 143) = 31.56$, $p < .001$, $\eta_p^2 = .57$, and group, $F(12, 444) = 3.79$, $p < .001$, $\eta_p^2 = .09$, on the postural control variables were found. The univariate contrasts showed a significant effect of block on EA, $F(2, 296) = 10.39$, $p < .001$, $\eta_p^2 = .07$; MV_{AP}, $F(2, 296) = 114.13$, $p < .001$, $\eta_p^2 = .43$; and MV_{ML}, $F(2, 296) = 8.77$, $p < .001$, $\eta_p^2 = .06$. The group variable had a significant effect on EA, $F(4, 148) = 9.01$, $p < .001$, $\eta_p^2 = .2$; MV_{AP}, $F(4, 148) = 3.34$, $p = .012$,

$\eta_p^2 = .08$; and MV_{ML}, $F(4, 148) = 8.0$, $p < .001$, $\eta_p^2 = .18$. Pairwise comparisons are reported in Tables 2 and 3.

Disturbance of Vestibular Information

Regarding bipedal quiet standing with a disturbance of vestibular information, a main effect of group, $F(12, 444) = 3.07$, $p < .001$, $\eta_p^2 = .08$, was found on the postural control variables. The univariate contrast revealed a main effect of group on EA, $F(4, 148) = 4.6$, $p = .002$, $\eta_p^2 = .11$; MV_{AP}, $F(4, 148) = 3.01$, $p = .02$, $\eta_p^2 = .07$; and MV_{ML}, $F(4, 148) = 6.67$, $p < .001$, $\eta_p^2 = .15$. Pairwise comparisons are presented in Figure 1, as well as the descriptive data of the postural control variables in the three blocks.

Disturbance of Proprioceptive Information

During quiet standing with a disturbance of proprioceptive information, the main effects of block, $F(6, 143) = 57.77$, $p < .001$, $\eta_p^2 = .71$, and group, $F(12, 444) = 3.37$, $p < .001$, $\eta_p^2 = .08$, were found on the postural control variables. An interaction effect between group and block was also found, $F(24, 584) = 1.54$, $p = .049$, $\eta_p^2 = .06$. The univariate contrasts are reported in Table 4. Pairwise comparisons

Table 2 Differences Between Blocks in Bipedal Standing With Restriction of Visual Information

	Block 1 (eyes open)	Block 2 (eyes closed)	Block 3 (eyes open)
EA (mm^2)	111.64 (108.16)*	153.18 (143.95)	109.02 (124.88)*
MV_{AP} (mm/s)	8.25 (2.49)*	10.89 (3.67)	8.19 (2.21)*
MV_{ML} (mm/s)	7.27 (2.45)*	7.85 (2.63)	7.13 (2.69)*

Note. EA = ellipse area; MV_{AP} = mean velocity in anteroposterior direction; MV_{ML} = mean velocity in mediolateral direction.
*Significant differences ($p < .05$) with Block 2.

Table 3 Differences Between Groups in Bipedal Standing With Restriction of Visual Information

	EA (mm^2)	MV_{AP} (mm/s)	MV_{ML} (mm/s)
13 years old	166.38 (139.99)	9.96 (3.22)	8.84 (3.29)
14 years old	185.50 (184.45)	9.71 (2.98)	8.01 (2.88)
15 years old	115.90 (87.48)**	9.32 (2.97)	7.47 (2.08)
16 years old	73.40 (61.70)*,**	8.11 (1.84)*	6.26 (1.38)*,**
17 years old	85.20 (56.56)*,**	8.50 (2.34)	6.58 (1.85)*

Note. EA = ellipse area; MV_{AP} = mean velocity in anteroposterior direction; MV_{ML} = mean velocity in mediolateral direction.
*Significant differences ($p < .05$) with 13-year-old group. **Significant differences ($p < .05$) with 14-year-old group.

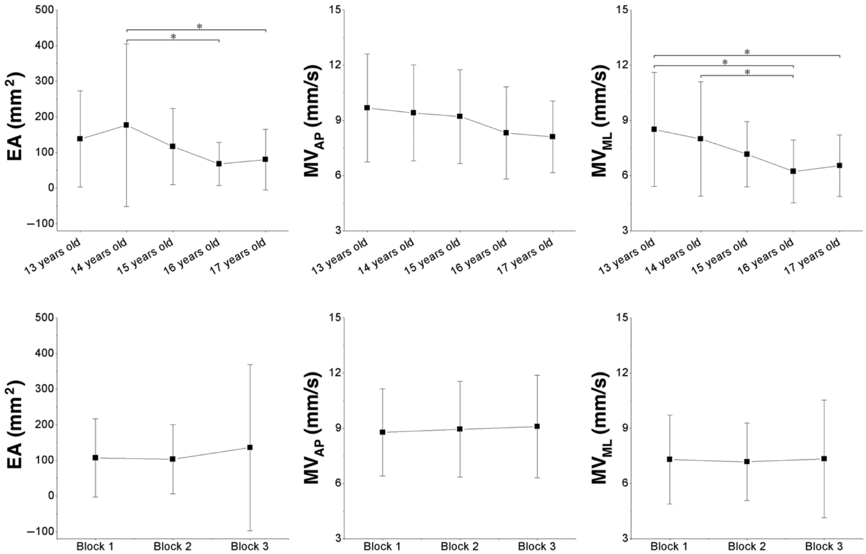

Figure 1 — Differences between groups and blocks in bipedal standing with disturbance of vestibular information condition. Squares represent the mean and error bars represent the *SD* of the mean. EA = ellipse area; MV_{AP} = mean velocity in anteroposterior direction; MV_{ML} = mean velocity in mediolateral direction. *Significant differences ($p < .05$).

revealed higher EA values in Block 2 than in Blocks 1 ($p < .001$) and 3 ($p < .001$), lower MV_{AP} values in Block 1 than in Blocks 2 ($p < .001$) and 3 ($p < .001$), and higher values in Block 2 than in Block 3 ($p < .001$). Meanwhile, higher MV_{ML} values were found in Block 2 than in Blocks 1 ($p < .001$) and 3 ($p < .001$). With reference to age group, pairwise comparisons showed higher EA values in 13- and 14-year-old children than in 16-year-olds ($p < .05$) and higher EA values in 13-year-olds than in 17-year-olds ($p < .01$). A lower MV_{AP} value was observed in 16- and 17-year-olds than in 13- ($p < .01$) and 14-years-olds ($p < .05$). In MV_{ML}, 13-year-olds showed higher values than 15- ($p < .05$), 16-, and 17-year-olds ($p < .01$). Finally, as presented in Table 4, there are only significant differences in the interaction between block and age group in the MV_{AP} variable, whose pairwise comparisons can be seen in Figure 2 and 3.

Discussion

The main objective of this study was to determine the differences in sensory reweight systems related to postural control during adolescence (i.e., between 13 and 17 years old) through the analysis of COP signals. First of all, our results found different postural control between subjects of 13–14 years old and older adolescents. Furthermore, a critical change was found in sensory reweighting during the bipedal stance with manipulation of proprioceptive information (i.e., vibration in the Achilles tendons) at 15 years old. The results indicate that

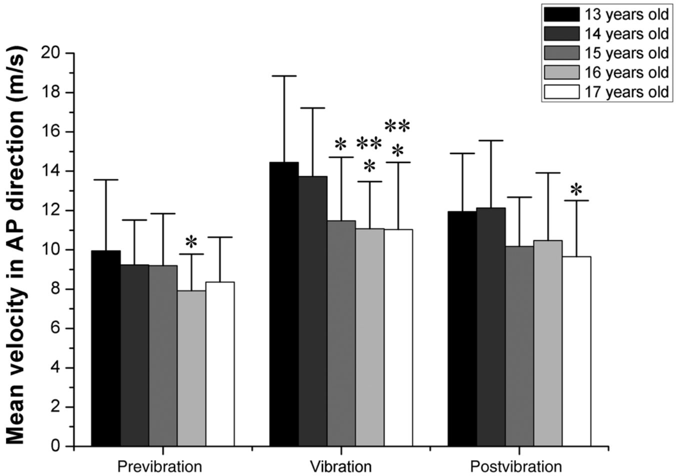

Figure 2 — Differences between groups in the three blocks of bipedal standing with disturbance of proprioceptive information. Bars represent the mean and the error bars represent the *SD* of the mean. AP = anteroposterior. *Significant differences ($p < .05$) in 13-year-old children. **Significant differences ($p < .05$) in 14-year-old children.

Table 4 Univariate Effects of Block and Group Age on the Postural Control Variables During Bipedal Standing With Disturbance of Proprioceptive Information

Effect	Variable	Degrees of freedom	*F* value	*p* value	η_p^2
Block	EA (mm^2)	2; 296	13.8	<.001	.85
	MV_{AP} (mm/s)	2; 296	103.1	<.001	.41
	MV_{ML} (mm/s)	2; 296	84.4	<.001	.36
Group age	EA (mm^2)	4; 148	5.19	.001	.12
	MV_{AP} (mm/s)	4; 148	5.95	<.001	.14
	MV_{ML} (mm/s)	4; 148	7.88	<.001	.18
Block × Group age	EA (mm^2)	8; 296	1.4	.2	.03
	MV_{AP} (mm/s)	8; 296	2.5	.01	.06
	MV_{ML} (mm/s)	8; 296	1.5	.16	.04

Note. EA = ellipse area; MV_{AP} = mean velocity in anteroposterior direction; MV_{ML} = mean velocity in mediolateral direction.

postural control variables, both in the open-eyes and closed-eyes conditions, were lower in the most advanced ages, which coincide with the fact that, as teenagers mature, their postural control is more similar to adults (Micarelli, Viziano, Augimeri, Micarelli, & Alessandrini, 2019). Concerning the visual restriction situation, the age of 15 appeared to be a turning point in the improvement of

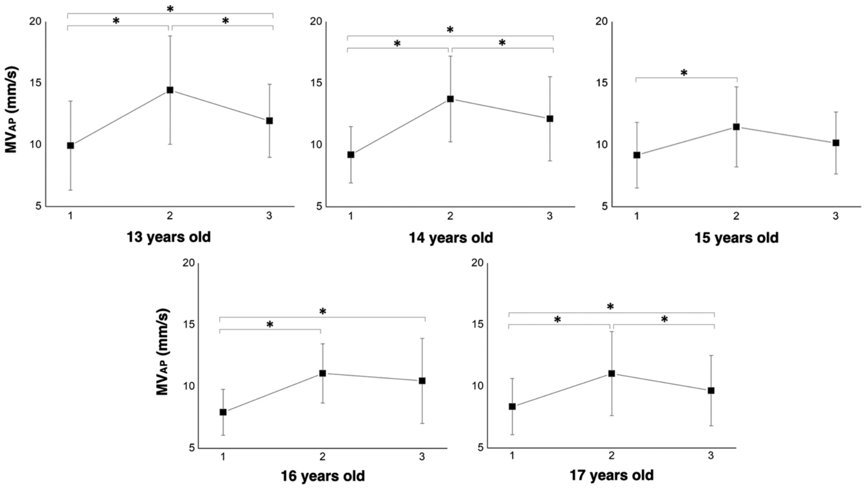

Figure 3 — Differences between blocks in each group in bipedal standing position with disturbance of proprioceptive information condition. Squares represent the mean, and error bars represent the *SD* of the mean. MV_{AP} = mean velocity in anteroposterior direction. *Significant differences ($p < .05$).

balance. Indeed, after this age, the results indicated that EA was lower for the older group than for the 14-year-old group. Furthermore, differences were found between the blocks (eyes open vs. eyes closed) in all ages, both in postural stability and control. This result is in line with those of previous studies in which lower postural stability (Hatzitaki, Zisi, Kollias, & Kioumourtzoglou, 2002) and control (Riach & Hayes, 1987) were found with eyes closed rather than with eyes open. However, the restriction of visual information affects adolescents equally, regardless of the age assessed. The results indicated that the youngest adolescents had lower postural stability and basically employed higher COP velocity, leading them to make bigger and faster displacements of the COP position than the older adolescents to maintain balance. The older adolescents presented a smaller EA and a lower mean velocity of COP displacements. These results are in line with previous studies, which have corroborated that the maturation of postural control is not observed until around 15 years, both in the condition of eyes open and eyes closed (Micarelli et al., 2019).

Regarding the manipulation of vestibular information, very similar results were found, indicating that the 16- and 17-year-old groups presented better postural control and/or stability than the 13- and 14-year-olds. This shows balance improvement with age. However, it is not known if this improvement arises from a development of the vestibular system or a development of individuals because of growth during adolescence. The results indicated that the manipulation of the vestibular system (using white noise) did not affect the ability to maintain postural stability during adolescence. Similar results had been found by other authors (Gandemer, Parseihian, Kronland-Martinet, & Bourdin, 2014), in which a stationary auditory stimulus of 83 dB did not influence postural control in adults. Borel and Ribot-Ciscar (2016) suggested that the vestibular system plays a minor role in achieving postural control in the static bipedal standing position in healthy subjects. The lack of differences between blocks could be explained by this less important role in this postural task. In addition, the way of presenting the sound influences balance; changes in the intensity and frequency of sound (Park, Lee, Lockhart, & Kim, 2011) or its movement characteristics (i.e., stationary or rotating sound source; Gandemer et al., 2014) influence postural control. Also, the presence and absence of sound in adults with eyes closed presented differences in relation to balance (Tanaka, Kojima, Takeda, Ino, & Ifukube, 2001; Welgampola & Colebatch, 2001). In addition, interindividual differences (e.g., physical activity status: active or nonactive) may influence postural responses to vestibular manipulation (Maitre & Paillard, 2016). It is, therefore, likely that the postural task characteristics and the difficulties in the proposed conditions are not sufficiently demanding to provoke changes in healthy adolescents.

Regarding the manipulation of the proprioceptive system, the results indicated that postural control and stability can be altered by vibration stimuli. As some authors previously observed, the application of vibration stimuli increases both the ellipse and the mean velocity of the COP (Ajrezo, Wiener-Vacher, & Bucci, 2013; Barozzi et al., 2014; Faigenbaum et al., 2014). In the present study, when vibratory stimuli were applied, young adolescents of 13 and 14 years of age presented higher MV_{AP} values than the 16- and 17-year-olds. As previously stated, our results also suggested the existence of a transition phase in the development of postural control around 15 years of age (Hirabayashi & Iwasaki, 1995). Three explanations might be suggested to clarify these postural differences. First, adolescents strengthen and increase the size of their muscles and tendons as they grow, and the muscle strength and volume of lower limb joints are highly and positively correlated with stability (Onambele, Narici, & Maganaris, 2006). Second, another explanation could be linked to the changes in the postural strategies of older adolescents, as they may have changed their strategy to use a more efficient one than younger participants (Brumagne, Cordo, & Verschueren, 2004). Third, another plausible explanation is that older adolescents may use other sensory systems than younger subjects to withstand proprioceptive manipulation and thus reduce the influence of erroneous proprioceptive information.

The results suggest that adolescents do not reach adult-like sensory reweighting in conditions in which proprioceptive information is altered until 15 years of age. This finding is in line with other studies, for example, Godoi and Barela (2008), who indicated that adults have better use of sensory inputs and better central nervous system integration than children, allowing children to improve their postural stability. The improvements in postural control may be due in part to the enhancement of the sensory reweighting ability. The ability to compensate and reweight the sensorial inputs develops after 11 years old (Cuisinier, Olivier, Vaugoyeau, Nougier, & Assaiante, 2011), with a stabilization period at around 15 years of age (Cuisinier et al., 2011; Peterka & Black, 1990). Even so, the reason for this change in postural control between adolescents and adults is still not known. According to Assaiante and Amblard (1995), children around 7–8 years old begin to use the same balance control strategies as adults (Assaiante & Amblard, 1995). Therefore, the difference of postural control between ages during adolescence might not be due to postural strategies. Some determining factors that may be influential are the possible differences in the use of sensory systems, strength, and muscular coordination (Groselj, Osredkar, Sember, & Pajek, 2019), as those elements are greater as the person develops.

As to the study limitations, the use of white noise to manipulate vestibular information did not produce changes in the postural control of adolescents. Therefore, future studies should use other methods, such as galvanic stimulations, to determine the effect of vestibular information manipulation on postural control and sensory reweighting. Another limitation found in this study is the different manipulations of the systems. While the visual system was completely restricted by closed eyes, the vestibular and proprioceptive systems were present and altered (adding noise or vibration). This difference could be a determining factor in the results, so we recommend that reweighting with the same degree of restriction or alteration of the systems should be studied in the future. In addition, future research could study each block in shorter periods to analyze the time taken to stabilize after a sensory alteration/restriction. Moreover, increasing the age range of the subjects would also be interesting to establish the period at which sensory reweighting is completely developed under conditions with visual restriction or vestibular manipulation. Finally, conditions like the manipulation of two resources of sensorial information could be interesting to further study the development of sensory reweighting during adolescence.

Conclusion

Thirteen- to fourteen-year-old adolescents showed less postural stability than older adolescents under conditions with manipulation of proprioceptive information, which may indicate that the sensory reweighting efficacy decreases and the sensory reweighting system stabilizes around 15 years of age. Moreover, a maturation of visual afference in postural balance was confirmed around 15–16 years old.

Acknowledgment

Garcia-Masso gratefully acknowledges the support of the Generalitat Valenciana under project GV2015-047.

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