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Original Article

Aging and the Relationship between Balance Performance, Vestibular Function and Somatosensory Thresholds

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OBJECTIVES: The objective of this study was two-fold: (1) To evaluate the impact of the physiological aging process on somatosensory, vestibular, and balance functions, and (2) To examine the extent to which age and somatosensory and vestibular functions can predict balance performance.

MATERIALS and METHODS: In this cross-sectional study, 141 asymptomatic subjects were assessed for touch pressure thresholds (TPT) with Semmes-Weinstein monofilaments (SWF), vibration thresholds (VT) with a neurothesiometer (NT) and a Rydel-Seiffer tuning fork 128Hz (RSTF). Horizontal vestibulo-ocular reflexes (HVOR gain and asymmetry) were assessed using the video Head Impulse Test (vHIT). A modified version of the Romberg test was used to assess standing balance and the Timed Up and Go test (TUG) and tandem gait (TG) to evaluate dynamic balance.

RESULTS: Significant age effects were found for TPT, VT, and balance but not for HVOR gain or asymmetry. Standing balance was explained for 47.2% by age, metatarsal 1 (MT1) (NT), and heel (SWF). The variance in TUG performance was explained for 47.0% by age, metatarsal 5 (MT5) (SWF), and medial malleolus (MM) (NT). Finally, the variance in TG performance was predicted for 43.1% by age, MT1 (NT), HVOR gain, and heel (SWF).

CONCLUSION: Among asymptomatic adult population, both somatosensation and balance performance deteriorate with aging. In contrast, HVOR remains rather constant with age, which is possibly explained by the process of vestibular adaptation. Furthermore, this study provides evidence that the VT, TPT, HVOR gain, and age partly predict balance performance. Still, further research is needed, especially with bigger samples in decades 8 and 9.

KEYWORDS: Healthy aging, postural balance, vestibule, labyrinth, touch, vibration

INTRODUCTION

Aging is one of the most significant challenges of the 21st century worldwide. People tend to get older because of better living conditions and medical progress, especially in developed countries. In Asia and Europe, the average life expectancy has surpassed 80 years. Moreover, people who are 85 years or older are the fastest growing age group in the United States. By the year 2025, worldwide, the number of people older than 60 years will exceed 1 billion. By the year 2050, this number will rise to 2 billion [1].

The elderly typically show reduced balance control [2], which is characterized by the central integration of sensory information mainly arriving from the vestibular, somatosensory, and visual systems for providing coordinated motor output. By the use of feedback and feedforward loop projections, the brain generates appropriate motor reactions. Memory, attention, and the constraints of the current environment and task will also contribute to these appropriate motor responses [2-4].

The process of aging is accompanied by natural physiological changes. Alterations arise in not only in the musculoskeletal system [3, 5], but also in the central and peripheral nervous systems. In the central nervous system, aging causes brain atrophy, reduced white matter connectivity and integrity, and activation of additional brain regions during complex motor tasks [6-8]. In the peripheral ner-

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vous system, communication between nerves abates, both the sensitivity and discriminative power of sensory receptors diminish, and the density of cutaneous receptors decreases. Specifically, vibration and proprioceptive perception both decrease with age and are related to a deterioration of postural control strategies [9]. In addition, it is well known that peripheral neuropathies often occur in individuals who are older than 65 years. This prevalence increases further when someone suffers from diabetes mellitus type II (DMII), which is common in older people [10]. Likewise, the vestibular system degenerates with age, causing a reduction in peripheral vestibular function and cortical efficiency [11].

Given these changes, it is not surprising that the risk of falling increases considerably when growing older. Moreover, this increased fall risk has important psychological repercussions such as depression, stress, anxiety, and fear of falling, which in turn will contribute to postural imbalance and the risk of falling, subsequently resulting in a reduced quality of life [3].

In summary, the aforementioned aspects show that alterations in balance control and related fall risk in older adults have a multifactorial origin. The visual function is known to deteriorate with aging, but the relative contribution to reduced balance control by the aging somatosensory and vestibular systems still remains under debate.

For example, Kristinsdottir and Magnusson [9] and Wiesmeier et. al. [12] hypothesized, respectively, that vibratory perception and proprioception contribute significantly to greater postural imbalance, while Ozdemir et. al. [13] pointed out the importance of vestibular dysfunction playing an important role. Furthermore, there is a paucity of detailed normative values for somatosensory thresholds in asymptomatic adults [14, 15] and a lack of insight into functional vestibular, age-related changes [16]. In this study, it is hypothesized that somatosensory function (touch pressure threshold [TPT] and vibration thresholds VTs]), vestibular function (high frequency horizontal canal function), and balance control worsen with increasing age [1]. In addition, it is hypothesized that the decrease in balance is related to alterations in the somatosensory and vestibular systems. Therefore, the primary goal of this study is to evaluate the impact of the physiological aging process on somatosensory, vestibular, and balance functions and second, to examine the extent to which age, somatosensory, and vestibular functions can predict balance performance.

MAIN POINTS

- Balance performance deteriorates and becomes more heterogeneous after the age of 50, dependent on the specific test used.
- Touch pressure and vibration thresholds increase after the age of 50 years.
- Horizontal vestibulo-ocular reflex (HVOR) gain tends to decrease after the age of 80.
- Age, vibration and touch thresholds, and HVOR gain are significant predictors of balance performance.

MATERIALS AND METHODS

Participants

In this cross-sectional study, healthy volunteers aged between 20 and 90 years were included. The reasons for exclusion included: (1) Actual complaints or a history of vertigo or dizziness; (2) Neurological, otological, orthopedic, or other medical conditions that could influence balance (e.g. diabetes); (3) Need of physical or material support; (4) A fall incident within the last 6 months; (5) Severe visual impairment such as cataract or glaucoma; (6) Current vestibular dysfunction; (7) Use of medication that can affect balance, including but not limited to sedatives, antidepressants, or antipsychotics; (8) Alcohol consumption or use of other stimulants within 24 hours before the test session; and (9) Not understanding the Dutch language. Subjects were recruited through personal contact, telephone, e-mail, and social media. The tests were carried out after all the subjects gave informed consent.

Study setup

The protocol consisted of somatosensory, vestibular, and balance testing and lasted for approximately 1 hour. The test protocol was performed by 4 researchers under the supervision of a physiotherapist with more than 30 years of experience.

This study took place at campus 'Drie Eiken' of the University of Antwerp between February 2018 and April 2019. The study protocol was approved by the Human Research Ethics Committee (B300201836268) of the University Hospital of Antwerp (UZA) and the University of Antwerp (UA).

Test procedure

Tests were performed in 2 different rooms with sufficient sound insulation to ensure optimal concentration. One room was exclusively used for measuring somatosensory outcomes. In the other room and adjacent corridor, subjects performed the vestibular and balance tests. All tests used in this study showed good and acceptable psychometric values [17-24]. To improve reproducibility and accuracy clusters of assessments, testing the same construct (somatosensation, balance, or vestibular function) was done by the same investigators. Subjects were tested on a level vinyl floor with adequate light and performed all assessments barefoot.

Somatosensory assessment

Blindfolded subjects remained comfortably seated during the protocol. They were allowed to move their feet regularly to prevent reduced blood flow and sleeping feet.

Touch pressure threshold

To determine TPT, Semmes-Weinstein monofilaments (SWF) (Advys, Waasmunster, Belgium) were used, 20 toothbrush-like monofilaments logarithmically ordered from thin (A; 1.65; 0.008g; 0.078mN) to thick (T; 6.65; 300g; 2941.176mN) [25]. Each monofilament corresponds to a certain letter, evaluator size or diameter, and a certain target force (expressed in grams or millinewton) summarized in the Appendix Table 1.

The modified 4, 2, and 1 stepping algorithm from Dyck and colleagues was used [26], in which the researcher gave 5 repetitive stim-

uli with one monofilament per step [22]. The application method was the same as Bradman's proposal [25]. Test sites on the plantar side of the foot were the center of the first distal phalanx (DP1), the head of the first metatarsal (MT1), the head of the fifth metatarsal (MT5), and the center of the heel. On the dorsal side of the foot, the instep and the first interosseal space (IS) were assessed. The same test order was maintained bilaterally.

Vibration threshold

The perception of the vibration threshold (VT) was evaluated using both a Rydel-Seiffer tuning fork 128Hz (RSTF) and a Horwell Neurothesiometer (NT: Algeos, Liverpool, UK). First, a quantitative RSTF was used ranging from 0 (minimum score) to 8 (maximum score). The RSTF was struck maximally and placed at the reference points till the vibration diminished. The subject said "yes" when vibration was no longer perceived. At that moment, the threshold corresponded with the nearest value of the intersection of the pyramids [21]. Secondly, an electronic NT with vibration frequency of 56Hz was used for the detection of VT [20]. The normal and most detailed range was used (0 to 50V). The voltage was slowly increased until the subject said "yes" (as soon as vibration was perceived) [27]. Lower VTs corresponded with lower NT scores, but with higher RSTF scores.

Thresholds were measured 3 times and averaged. Three different anatomical locations were assessed bilaterally; tuberositas tibiae (TT), medial malleolus (MM), and the dorsal side of the head of the first metatarsal (MT1). The same test order was maintained for each person.

Vestibular assessment

The vestibulo-ocular reflex (VOR) was assessed using the video Head Impulse Test (vHIT). The vHIT offers objective measurements for high-frequency vestibular semi-circular canal function. In this study, the data collection focused on the horizontal VOR (HVOR) gain and the percentage asymmetry between left and right HVOR, indicated by HVOR asymmetry. A target was placed 1.5 m away from the subject for eye-fixation during the test. Before testing, the software was calibrated. During passive horizontal head movements [28, 29], eye and head velocities were registered. Subsequently, HVOR gain and asymmetry were automatically computed by the specialized EyeSeeCam software (Autronic, Hamburg, GE) [29]. Subjects were excluded if low gains and corrective saccades were present.

Care was taken to avoid artifacts, such as blinking or goggle slippage, that might corrupt the measurements [29, 30]. A retest was performed when uncertainties or too many artifacts were detected, within the same test session, but after recalibration of the device.

Balance assessment

The proximity of a researcher was guaranteed to minimize fall risk while performing standing and dynamic balance tests.

Standing balance: For the assessment of standing balance, participants performed a test protocol that consisted of 4 modified Romberg test conditions with increasing difficulty [17], performed performed 3 times with eyes open (EO) and eyes closed (EC) with the instruction to maintain each position as long as possible:

1. Classical Romberg test with Jendrassik maneuver with EO (ROMeo). and EC (ROMec).
2. Feet parallel with Jendrassik maneuver on a medium density foam pad with EO (SOFeo) and EC (SOFec). A standardized foam pad with medium density (60 kg/cm^3) was used (45cmx45cmx12cm, NeuroCom International Inc., Clackamas, USA).
3. Tandem stance on a firm surface with EO (TReo) and EC (TRec).
4. Single leg stance on a firm surface with EO (SLSeo) and EC (SLSec).

During TR and SLS, the subjects were permitted to choose the stance leg (i.e. SLS), the leg they placed in front (i.e. TR), and to change legs between trials. The time started when a person stood steadily in the requested position and stopped when the person deviated from the test guidelines or when the 30-second limit was reached. The best of 3 trials was the final score. As a global measure of standing balance (standing balance sum (SBS)), the sum of the 8 test conditions (4 positions, both with EO and closed) was taken, resulting in a maximum score of 240.

Dynamic balance

Both the Timed Up and Go (TUG) and the tandem gait test (TG) were assessed to evaluate dynamic balance. The TUG was performed following a standardized protocol [18, 19]. Instructions, a demonstration, and a practice trial were done prior to testing. Subsequently, each subject was allowed 3 timed trials, with the fastest performance being used as the final score. For the assessment of TG, each subject had to walk 20 consecutive heel-to-toe steps in a straight line (i.e., tapeline on the floor). The total number of steps was counted until the maximum score of 20 steps was reached or if a person took a diverging step from the tapeline, touched the wall, or did not touch the toes with the heel. Three trials were permitted, except when the maximum score was achieved earlier, and then the test was stopped after the first or second trial. The number of correctly performed steps were counted, and the best performance was considered for analysis [31, 32].

Statistical Analysis

Analyses were performed with the Statistical Packages for the Social Sciences (SPSS) version 26 (IBM Corp., Armonk, NY, USA). Data were checked for quality by searching for missing data and outliers. Outliers were determined via boxplots and excluded when influencing results significantly. Missing data were manually checked for errors. Descriptive statistics were determined for all subjects. As there were no statistical differences between left and right vestibular and somatosensory values, confirmed by a paired t-test ($p>0.05$), means were calculated for left and right (TPT, NT, RSTF and HVOR gain). These mean values were used for further analysis.

The analyses considering TPT as measured by SWF, were executed on the "filament numbers" ranging from 1 to 20 corresponding to the letters of each filament A to T (column 1 in the Appendix Table 1). This conversion was done to correct for violations of normality and homogeneity. Decades, ranging from 3 to 9, were established to subdivide subjects into specific age groups.

Normality of data was checked by visual inspection and a Kolmogorov-Smirnov test. Parametric tests were applied on continuous variables if the sample contained 30 or more subjects or if variables were normally distributed. If the sample contained less than 30 subjects and the variables were not normally distributed, nonparametric tests were chosen.

Table 1. General subject characteristics

Decade	N	Age (years) mean±SD	Age (years) Range	Gender F:M	Body length (m) mean±SD	Body weight (kg) mean±SD	BMI (kg/m²) mean±SD
Tot.	141	50.52±17.88	22.00–88.05	82:59	1.72±0.10	70.44±11.60	23.96±2.81
3	29	24.39±1.80	22.00–29.55	19:10	1.74±0.09	67.39±10.40	22.08±1.96
4	13	34.43±2.93	30.48– 39.73	6:7	1.76±0.09	71.67±13.36	22.95± 3.03
5	14	46.30±2.19	42.93–49.25	8:6	1.76±0.11	75.39±16.20	24.12±3.25
6	44	54.69±2.64	50.08–59.88	29:15	1.70±0.08	70.46±10.89	24.28±2.72
7	21	63.96±2.45	60.21–68.41	9:12	1.71±0.09	73.60±10.08	25.15±2.54
8	11	75.11±3.05	71.21–79.29	6:5	1.66±0.10	68.41±10.27	24.72±3.00
9	9	82.72±2.19	80.67–88.05	5:4	1.64±0.09	65.83±11.12	24.41±2.65

The impact of aging on the somatosensory variables (NT, RSTF and SWF), vestibular variables (HVOR gain and HVOR asymmetry), standing balance (ROMeo, ROMec, SOFeo, SOFec, TReo, TRec, SLSeo and SLSec), and dynamic balance (TUG and TG) was established in 2 steps. First, Pearson correlation coefficients were calculated between these variables and age. Second, Kruskal-Wallis tests (nonparametric), along with the Mann-Whitney U test as post hoc analysis with Bonferroni-correction, were performed to identify differences across decades.

Finally, to examine the extent of age at which somatosensation and vestibular function predict balance performance, 3 stepwise regression analyses were applied. The dependent variables were the SBS, the TUG, and TG performance. The variable age and all somatosensory and vestibular variables were implemented in the regression analyses as independent variables.

Level of significance was set at 0.05.

RESULTS

Participants

In this cross-sectional study, 150 healthy subjects aged between 20 and 90 years were recruited. Nine persons (8 women and 1 men) were excluded from the protocol because of the use of drugs (such as antidepressants and sedatives) (n=6), abnormal vestibular function (based on unilateral low gains with the presence of corrective saccades) (n=2), and the inability to concentrate during the test sessions (n=1). One hundred and forty-one subjects were eligible for analysis, of which 137 subjects were tested with NT and 139 subjects with vHIT. Data were lacking because of battery (i.e. NT) (n=2) and/or registration problems (i.e. vHIT) (n=4). Characteristics of the sample are summarized in Table 1.

The impact of aging on somatosensation, horizontal vestibular function, and balance performance

Somatosensation

Touch pressure threshold

Depending on the test location, statistically significant ($p<0.01$) weak-to-moderate correlations were found between age and TPT. Weak correlations were found between age and DP1 ($r=0.35$), the instep ($r=0.37$), and MT1 ($r=0.39$). Age correlated moderately with IS ($r=0.44$), heel ($r=0.50$), MT5 ($r=0.52$), and with the summed scores of all test locations ($r=0.50$).

Table 2 reveals that with increasing age thresholds, each reference point tends to increase steadily and significantly (Kruskal-Wallis analysis $p<0.01$). Reference points DP1 and IS showed the lowest median value of 4.00 (decade 3) corresponding with filament "D," while the highest median threshold (10.00, corresponding with monofilament "J") was observed at the heel, MT5, MT1, and DP1 (in decades 5, 7, 8, and 9). Post hoc analysis (Appendix Table 2) showed the largest number of statistically significant differences between specific decades when the heel was used as a reference point, followed by MT5, especially between the older (6th to 9th decades) and the younger (3rd and 4th decades) adults.

Vibration threshold

The Pearson correlation between the outcomes measured by NT and RSTF was strong, but negative ($r=-0.74$; $p<0.01$).

Neurothesiometer

Strong positive correlations were found between the test results of the individual reference points, their summed score and age, ranging from 0.61 to 0.68 ($p<0.01$).

For reference points MM and MT1, a first increase in the VT is shown in decade 6 followed by a significant secondary increase in the 8th decade (Table 3). Post hoc analysis confirmed these observations with significant differences ($p<0.05$) for MM and MT1 between decades 3 and 4 and significant difference between the 5th and 6th decade versus decades 8 and 9 (Appendix Table 3). Similar but less explicit results could be observed for TT (Table 3 and Appendix Table 3).

Rydel-Seiffer tuning fork

In general, similar conclusions can be made for RSTF compared to NT. For all reference points and the summed score, significant moderate negative ($p<0.01$) correlations with age were found varying from –0.38 to –0.53. Table 3 shows an increase of thresholds, especially from decade 7 onwards (Kruskal-Wallis $p<0.01$), for all reference points. However, Mann-Whitney U analysis could only reveal significant differences between decade 3 versus 7 to 9 and between 6 versus 7 to 9, mainly at MM ($p<0.05$) (Appendix Table 3).

Table 2. Median and inter quartile range for touch pressure threshold measured by Semmes-Weinstein monofilaments per decade for each reference point

Decade	N	DP1 median (IQR)	MT1 median (IQR)	MT5 median (IQR)	Heel median (IQR)	Instep median (IQR)	IS median (IQR)
Tot.	141	6.00 (4.50–9.50)	7.50 (5.00–10.00)	7.50 (5.50–10.00)	8.50 (6.50–10.50)	5.50 (4.50–8.00)	4.50 (4.00–7.00)
3	29	4.00 (3.50–7.50)	5.00 (4.00–7.00)	5.00 (3.50–6.75)	5.00 (4.00–7.25)	4.50 (3.50–5.50)	4.00 (3.25–4.50)
4	13	5.00 (4.25–8.50)	6.00 (5.00–10.00)	5.50 (5.00–7.50)	5.50 (5.25–7.75)	5.00 (4.25–6.50)	4.50 (4.00–6.00)
5	14	6.50 (4.50–8.38)	7.50 (5.75–10.13)	7.75 (5.38–10.13)	10.00 (6.38–10.63)	6.25 (4.50–8.50)	5.75 (4.00–7.13)
6	44	6.50 (4.50–8.38)	7.75 (5.63–10.00)	8.25 (6.50–10.00)	9.50 (7.50–10.38)	5.00 (4.13–7.88)	4.50 (4.00–6.38)
7	21	7.50 (5.00–10.50)	8.00 (5.50–10.25)	8.50 (7.25–10.00)	10.00 (7.00–10.75)	6.00 (4.25–8.75)	4.50 (4.00–7.75)
8	11	7.00 (6.00–10.00)	10.00 (7.00–11.00)	10.00 (8.50–11.50)	9.00 (8.00–11.50)	8.00 (6.50–9.50)	8.00 (4.50–9.50)
9	9	10.00 (5.00–11.50)	9.50 (7.75 – 11.25)	10.00 (7.75–13.25)	10.00 (8.25–13.25)	8.00 (5.00–10.00)	8.00 (5.50–10.25)
Sig. (p)		<0.01**	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**

**p<0.01; DP1: first distal phalanx; MT1: head of first metatarsal; MT5: head of fifth metatarsal; IS first interosseal space; IQR: interquartile range; Tot.: whole sample; n: number of subjects; Sig.: significance determined by Kruskal-Wallis analysis.

Table 3. Median and inter quartile range for VT per decade for each reference point

		NT (voltage)				RSTF		
Decade	N	TT median (IQR)	MM median (IQR)	MT1 median (IQR)	N	TT median (IQR)	MM median (IQR)	MT1 median (IQR)
Tot.	137	9.50 (6.88–12.25)	7.83 (5.21–11.96)	5.08 (2.88–8.38)	141	5.42 (4.60–5.98)	5.75 (4.58–6.45)	5.90 (4.44–6.83)
3	29	6.92 (5.29–8.58)	4.67 (3.88–6.75)	2.67 (1.79–3.58)	9	5.50 (4.94–6.40)	6.38 (5.38–7.08)	6.83 (5.10–7.52)
4	13	9.50 (6.75–11.38)	6.33 (5.13–7.08)	2.92 (2.17–4.21)	13	5.46 (4.98–5.81)	5.75 (5.50–6.38)	6.21 (5.79–6.54)
5	14	6.83 (6.04–11.13)	7.17 (4.79–9.21)	4.83 (2.44–7.19)	14	5.83 (5.05–6.33)	6.27 (5.45–6.85)	6.08 (5.61–6.98)
6	43	9.67 (7.75–11.50)	8.42 (6.00–10.25)	5.00 (3.33–8.33)	44	5.58 (5.19–6.04)	5.92 (5.49–6.36)	6.06 (5.09–6.70)
7	19	12.67 (9.50–15.83)	11.67 (7.50–18.42)	7.67 (5.83–12.08)	21	4.50 (3.69–5.33)	4.33 (3.44–5.51)	4.50 (3.38–5.87)
8	11	14.33 (10.58–20.25)	20.42 (14.33–25.25)	14.17 (8.17–19.92)	11	4.42 (3.25–5.17)	3.17 (2.42–5.42)	3.83 (2.42–5.21)
9	8	25.79 (18.08–33.79)	26.29 (13.58–31.13)	14.33 (13.02–29.19)	9	4.42 (2.40–5.79)	3.75 (2.55–4.81)	3.67 (1.68–5.50)
Sig. (p)		<0.01**	<0.01**	<0.01**		<0.01**	<0.01**	<0.01**

**p<0.01; NT: neurothesiometer; RSTF: Rydel-Seiffer tuning fork; TT: tuberositas tibiae; MM: malleolus medialis; MT1: head of metatarsal 1; IQR: interquartile range; Tot.: whole sample; n: number of subjects; Sig.: significance determined by Kruskal-Wallis analysis.

Table 4. Median and inter quartile range for HVOR gain and HVOR asymmetry

Decade	N	HVOR gain median (IQR)	HVOR asymmetry (%) median (IQR)
Tot.	139	1.02 (0.94–1.08)	0.00 (−2.00–2.00)
3	29	1.04 (0.98–1.10)	1.00 (0.00–4.00)
4	13	1.01 (0.96–1.05)	−1.00 (−2.50–0.50)
5	14	1.05 (1.00–1.08)	0.00 (−2.25–1.00)
6	44	0.99 (0.91–1.08)	0.00 (−2.00–2.00)
7	21	1.00 (0.94–1.06)	0.00 (−2.50–3.00)
8	11	1.02 (0.92–1.09)	0.00 (−2.00–2.00)
9	9	0.83 (0.75–1.01)	−0.50 (−6.50–3.50)
Sig. (p)		0.09	0.15

**p<0.01; HVOR: horizontal vestibulo-ocular reflex; IQR: interquartile range; Tot.: whole sample; N: number of subjects; Sig.: significance determined by Kruskal-Wallis analysis.

Horizontal vestibular function

The correlations between vestibular function and age were not significant (p>0.05).

Table 4 shows median HVOR gains of approximately 1.00 in all decades, except for decade 9. The decrease to 0.83 in decade 9 (n=9) was not proven significant (p>0.05). Median values for HVOR symmetry varied from –1 in decade 4 to 1% in decade 3. The interquartile range (IQR) increased from 3% in decade 4 to 10% in decade 9. Kruskal-Wallis analysis confirmed no significant differences between the decades for HVOR gain (p=0.21), and for HVOR symmetry (p=0.15). However, variability increased with increasing age as evidenced by larger IQR.

Balance

Standing Balance

All subjects performed the ROMeo condition maximally; therefore correlations with age could not be calculated. Correlations among age, ROMec, and SOFeo were negligible and insignificant (p>0.05). The

Table 5. Median and inter quartile range of standing and dynamic balance conditions

		Standing balance (seconds)					Dynamic balance (locomotion)	
Decade	N	SOFec median (IQR)	TRec median (IQR)	SLSeo median (IQR)	SLSec median (IQR)	SBS median (IQR)	TUG (s) median (IQR)	TG (steps) median (IQR)
Tot.	141	30.00 (30.00–30.00)	30.00 (11.76–30.00)	30.00 (30.00–30.00)	18.52 (6.38–30.00)	224.87 (207.76–240.00)	5.35 (4.69–6.10)	20.00 (20.00–20.00)
3	29	30.00 (30.00–30.00)	30.00 (29.50–30.00)	30.00 (30.00–30.00)	30.00 (30.00–30.00)	240.00 (236.09 – 240.00	4.69 (4.47–5.04)	20.00 (20.00–20.00)
4	13	30.00 (30.00-30.00)	30.00 (20.23–30.00)	30.00 (30.00–30.00)	30.00 (14.11–30.00)	226.15 (218.28–240.00)	4.26 (3.80–5.16)	20.00 (20.00–20.00)
5	14	30.00 (30.00-30.00)	30.00 (27.98–30.00)	30.00 (30.00–30.00)	30.00 (24.37–30.00)	235.97 (225.22–240.00)	5.26 (4.72–5.70)	20.00 (20.00–20.00)
6	44	30.00 (30.00-30.00)	30.00 (22.52–30.00)	30.00 (30.00–30.00)	16.08 (9.82–30.00)	225.41 (213.62–237.85)	5.30 (4.79–5.89)	20.00 (20.00–20.00)
7	21	30.00 (30.00-30.00)	19.65 (8.61–30.00)	30.00 (25.40–30.00)	5.60 (3.96–14.98)	194.58 (187.45–194.58)	5.71 (5.26–6.51)	20.00 (20.00–20.00)
8	11	30.00 (30.00-30.00)	7.80 (4.50–11.82)	19.65 (8.61–30.00)	3.30 (1.81–4.73)	182.79 (162.51–192.97)	7.63 (7.16–8.38)	20.00 (5.00–20.00)
9	9	30.00 (7.13-30.00)	8.66 (1.48–20.15)	14.40 (3.84–21.83)	0.00 (0.00–5.41)	172.36 (131.68–183.77)	8.70 (7.82–9.95)	6.00 (2.00–15.50)
Sig. (p)		<0.01**	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**	<0.01**

**p<0.01; SOF: stand on foam test; TR: tandem Romberg; SLS: single leg stance; eo: eyes open; ec: eyes closed; SBS: standing balance sum; TUG: Timed Up and Go; TG: tandem gait; IQR: inter-quartile range; Tot.: whole sample; N: number of subjects; Sig.: significance determined by Kruskal-Wallis analysis.

remaining correlations varied from –0.25 to –0.67 ($p<0.01$), with r_{SLSec} being the highest. SBS correlated strongly with age ($r=-0.65$; $p<0.01$).

Table 5 reveals that scores under test conditions SOFec, TRec, SLSeo, SLSec, and SBS reduced significantly as subjects got older (Kruskal-Wallis $p<0.01$). For the separate balance conditions, median values dropped from 30s to 19.65s for SLSeo in the 8th decade, from 30s to 19.65s for TRec in the 7th decade, and from 30s to 16.08s for SLSec in the 6th decade. Significant differences among decades are shown in Appendix Table 4. SBS and SLSec reveal similar age-related differences (Appendix Table 4).

Dynamic balance

Age correlated moderately with TG ($r=-0.50$, $p<0.01$) and strongly with the TUG ($r=0.67$; $p<0.01$). Table 5 shows that performances of both TUG and TG worsen with increasing age (Kruskal-Wallis analysis $p<0.01$). Post hoc analysis shows that TUG times increase significantly from decade 6 onwards (Appendix Table 5).

All adults up to decade six were able to perform the TG test maximally. Two subjects in their sixties performed submaximally, but this finding was insignificant ($p>0.05$). Nevertheless, the septuagenarians and octogenarians performed significantly poorer (Appendix Table 5) and were more variable (IQR: 5–20; 2–15.50) when compared with the younger adults.

The relationship between balance, somatosensation, horizontal vestibular function, and age

Pearson correlations between balance and TPT varied from –0.18 to –0.35 ($p<0.05$), between balance and NT from 0.31 to –0.58, between balance and RSTF from –0.27 to 0.47 ($p<0.01$), and, between balance and HVOR gain from 0.24–0.28 ($p<0.01$). Correlations were negligible and insignificant, ranging from 0.08 to 0.16 ($p>0.05$) between balance and HVOR asymmetry as well as between dynamic balance (TUG, TG) and DP1 (TPT). All 3 stepwise linear regression models were significant ($p>0.01$) with R^2 ranging from 0.431 to 0.472. The variance of the summed score of standing balance was explained for 47.2% by age, MT1 (NT), and heel (SWF). The variance of TUG performance was explained for 47.0% by age, MT5 (SWF), and MM (NT). Finally, the variance of TG performance was predicted for 43.1% by MT1 (NT), HVOR gain, and heel (SWF).

DISCUSSION

Decreased balance control in an aging population is an important challenge in the 21st century. Mechanisms underlying adequate balance control are multifactorial, and the effect of aging is not entirely understood [2]. This study provides insight into the impact of the physiological aging process on somatosensation, vestibular function, and balance performance in an asymptomatic population. New insights have been gained into which factors explain balance and which variables are important for adequate balance performance.

The impact of aging on somatosensation, horizontal vestibular function, and balance performance

Generally, TPT, VT, and balance have a moderate-to-strong correlation with age and show significant age-related effects. A decline in performance was evident from the 6th decade, but became more pronounced in decade 7, (i.e., as soon as age 60 was exceeded). Generally, both correlations and age effects were negligible for HVOR, but in decade 9 a decline could be observed. Aging is a natural process that is assumed to have its effect on all aspects of the human body; however, differences between physiological and nonphysiological phenomena are still difficult to discriminate [33]. Unraveling this difference is especially challenging as people of older age nearly always show multimorbidity [34]. In this study, known comorbidities that possibly influenced balance control were excluded in advance. For example, adults diagnosed with a form of diabetes were excluded prior to assessment. Therefore, our values may be considered as physiological changes and consequently provide additional insights into which values are nonphysiological. Nevertheless, unknown abnormalities may still be evident as adults may suffer from an undiagnosed pathological or abnormal condition. More specifically, adults, especially in older age, may suffer from pre-diabetes which is an undiagnosed form of diabetes [35] that may have remained unknown in our study. Furthermore, our results demonstrated a large variability

after the age of 50, which may indicate that both people with and without a specific problem may be present within one decade because people age in different ways.

Somatosensation

Age-related changes for both TPT and VT are confirmed by earlier research [14, 15, 36]. Peripheral somatosensory problems can occur with distal peripheral neuropathies. Neuropathies are common with aging, and the prevalence increases when people suffer from DMII [37, 38]. Adults with diagnosed diabetes were excluded prior to inclusion to minimize the effect of this pathology on results and to ensure an asymptomatic sample. Excluding these subjects was particularly important, considering that approximately 20% of adults older than 65 years are diagnosed with DMII [39].

When assessing TPT, the most frequently mentioned cut-off value for screening distal neuropathies in patients with DMII is monofilament 5.07/10g (corresponding with filament 14/N in the 20-piece kit). Still, this cutoff value remains under debate [40]. In this study, based on the scores on all test locations, 1 subject (decade 9) was considered as having bilateral distal neuropathy, while 2 additional subjects showed a higher score than filament N only at both DP1s (decade 7). Abnormal VTs, identified by a higher value than 25V (NT), can indicate future foot ulceration risk in patients with DMII [41]; and thus, 3 subjects in our sample showed risk of foot ulceration. In summary, as might be expected, a small percentage of participants showed results suggesting abnormality. This may be related to an undiagnosed form of DMII. However, most included adults showed age-related changes in older age that were not associated with pathological conditions, suggesting physiological changes. Normative values for RSTF are currently lacking, and generally there is a lack of standardization for assessing both TPT and VT, making comparison with other study results rather difficult [27, 40].

Horizontal vestibular function

Nearly 50% of adults over the age of 60 show some form of vestibular physiological loss [16]. This age-related reduction in vestibular function, called presbyvestibulopathy, is related to imbalance and falls [16, 42]. In literature, HVOR gains (vHIT) bilaterally between 0.60 and 0.80 may indicate presbyvestibulopathy [42]. In the present study, the HVOR gain remained constant from 20 till 80 years with median values close to 1.00 which is considered normal [29]. Although the median gain value decreased to 0.83 in decade 9, it did not differ significantly from the medians in the other decades. The lack of significance is probably because of the small sample in decade 9 (n=9). Three octogenarians did show gains below 0.80, suggesting the presence of presbyvestibulopathy, but 5 showed gains above 0.80 which suggest physiological gains. Nevertheless, a small number of participants less than 80 years (n=5) showed scores between 0.60 and 0.80, indicating that asymptomatic vestibular deficiencies are apparent at all ages, which is in line with previous findings of Yang et al. [43]. However, literature is inconclusive on whether HVOR gain deteriorates with aging. Both Yang et al. [43] and McGarvie et al. [44] showed nil or small age-related alterations in HVOR gain. In contrast, other authors did find age-related changes. Mossman et al. [45] observed a decrease of 0.012 and 0.17 per decade measured at 60 ms and 80 ms, respectively. Two other studies showed a decline at older age, one from 80 years on [46], and the other after 90 years [47], indicating that with the very elderly, low gains related to presbyvestibulopathy might be expected [46, 47]. These findings suggest that the observed decline of HVOR gain in decade 9 could be significant if the sample were larger. Additionally, median scores of HVOR asymmetry remained quite constant over age, varying from -1% to 1%; however, variability increased considerably with increasing age as indicated by the increasing IQR. Both the decline in HVOR gain and the increase in variability of HVOR asymmetry indicate some underlying physiological changes as individuals age.

Balance

Likewise, balance performance decreases with age, starting in decade 6, but with a more marked decline from decade 7 as seen by SBS. The association between standing balance and age was the strongest for SLSec, followed by TRec, SLSeo, SOFec, and TReo. The condition ROMeo was the easiest and performed maximally by all subjects. Conversely, condition SLSec could discriminate best between the different age groups and was the first condition in which the subjects showed a submaximal performance as their age increased. This is in agreement with the data provided by Vereeck and coworkers, where the single leg stance with EC was perceived as the most difficult, followed by TRec [17]. People in decade 3 and 4 should be able to perform condition SLSec for 30 seconds. However, 5 subjects in their twenties and 5 in their thirties showed anomalous results as they did not reach this limit [17]. Two people in decade 5 and 9 people in decade 6 performed submaximally in condition TRec. Finally, people in decade 7 and 8 should be able to last for 30 seconds in condition SOFec, a criterion that was not reached by 2 subjects (17). We therefore speculate that these people may be more susceptible to imbalance and the risk of falling.

Dynamic balance also deteriorates with age. The decline of TUG performance could be observed at decade 6, but became more pronounced around decade 7, which is in line with the standing balance. A score higher than 10 seconds indicates a higher risk of falls [48]; however, thresholds vary from 10 to 33 seconds in the literature [49]. Following the 10-second threshold, our findings reveal that 4 subjects aged 75–83 years performed abnormally slow, indicating poor dynamic balance.

Concerning TG performance, all subjects below the age of 60 performed the TG maximally, but results became more variable in decade 7 and decade 9, and no subject could perform this test maximally. Thus, as they got older, more people achieved high scores for TUG performance and performed submaximally on the TG, which is confirmed by earlier research [17, 32, 50].Walking with a narrow base of support, like in the TG test, is often reported differently, which makes comparison with other findings challenging. However, as not all subjects in decade 8 (n=6) and 9 (n=1) were able to perform 20 consecutive heel-to-toe steps, this test is probably too challenging for people at older age and does not necessarily indicate abnormalities at older age. This indicates that modifications of the test are required. Performing only TG with 10 steps and with EC, as proposed by Cohen et al. [31, 32], may be a more sensitive measure to see differences between each decade instead of performing this test only with EO, but this needs further investigation. In our sample, 2 octogenarians performed submaximally on both the standing balance tests and the dynamic balance tests (TG & TUG), implying that these adults have poor balance control and are highly susceptible for falls.

Relationship between balance, somatosensation, horizontal vestibular function, and age

Since mechanisms underlying balance control are multifactorial (e.g., correct sensory integration, adequate muscle control, biomechanical constraints, and cognitive aspects), it is challenging to identify which factors are important for assuring adequate balance control [2].

Of all included sensory parameters (somatosensory and vestibular), vibration (NT) was the strongest correlator with both standing and dynamic balance performance, which implies that balance performance and vibration sensitivity are significantly interrelated. Moreover, SBS and TUG performance were mainly predicted by both vibration and touch, measured at different lower limb test locations. Kristinsdottir and Fransson [9, 51] provided evidence that vibration is a significant predictor for increased postural sway with even greater effects when vibration stimuli were given during standing balance tests. It is suggested that plantar vibration might improve performance of TUG in stroke patients, which confirms an association between vibration sense and balance [52].

Likewise, the variance in TG performance was mainly predicted by vibration and touch, and was additionally influenced by HVOR gain. Cohen et. al. [32] found that vestibular problems could be screened with the tandem walking test in patients with vestibular disorders with a sensitivity of 0.77 and specificity of 0.72, which confirms a relation between vestibular function and performance of the TG. Another study of Cohen et al. [31] demonstrated that the TG test is also a good screening tool for assessing peripheral neuropathies (i.e. somatosensory problems), which can clarify why touch and vibration explain the variance in TG, even in asymptomatic adults.

Furthermore, age was a factor that partly explained outcomes in all 3 balance tests. This may reflect the impact of other age-related physiological and structural alterations in the body (other than structures assuring TPT, VT, or HVOR) such as loss in muscle strength or altered muscle control which may also influence balance performance. Indeed, it is suggested that older adults show different strategies in the use of ankle muscles to maintain bipedal stance compared to younger adults [53], which implies that these aspects are also important to maintain balance.

Numerous structural and physiological alterations can be observed in the nervous system when aging [33]. Changes occur in the brain, nerve fibers, and corpuscles in the skin that consequently make the processing of touch and vibration more challenging and less adequate. In addition, neurological structures (vestibular receptor cells, primary afferents, efferent nerves, synapses, commissural fibers, cerebellum, thalamus, and brain stem nuclei) involved in providing adequate HVOR show structural changes because of aging [16]. However, finding a correlation between these structural changes and functional outcome is often difficult and has been debated [54]. In the current study, statistically insignificant age-related changes of the vestibular system were found (HVOR gain and asymmetry), which can provide evidence of vestibular adaptation during the aging process, resulting in functional changes that remain subclinical, even if structural changes are present in the vestibular system [44].

In order to achieve, maintain, or restore balance, sensory reweighting is an important phenomenon that refers to the change in the relative contribution of the different sensory modalities [55]. However, when sensory information is no longer available, less options are available to ensure sufficient balance control. Since older adults might suffer from vestibular, somatosensory, and visual (such as retinopathy in patients with DMII) problems, it is likely that adequate sensory reweighting may be in danger, consequently resulting in a larger risk of balance problems and fall incidents [56]. This risk will increase further when other problems co-occur with those sensory problems, such as loss in muscle strength or diminished muscle control.

Clinical implication

A few recommendations for clinical practice can be summarized. Assessing somatosensation (by SWF and NT), vestibular function (vHIT), and balance (Romberg, TUG, and TG) provide complementary information regarding normal physiological age-related changes, but additional assessments, such as the evaluation of muscle strength or muscle activation patterns [53], may be required to provide a more comprehensive view on aging and balance performance. Furthermore, it is recommended to test both standing and dynamic balance as they measure different constructs [2].

Because of the strong correlation between RSTF and NT, we conclude that they measure the same construct. Choosing one device to assess VT is therefore permitted. NT is preferred over RSTF for assessing VTs as NT shows a stronger association with both age and balance and is better at determining age-related changes. Assessing VT must be complemented by assessing TPT. Raymond et. al. [27] suggested combining NT and SWF because of a better diagnostic capacity compared to the combination of SWF and a 128 Hz tuning fork to assess diabetic neuropathies. To improve standardization for evaluating both TPT and VT [27, 40], we recommend assessing reference points MT5, heel, and IS to determine TPT (with SWF), while with NT, only assessing at the level of the MM is necessary to determine VT. These reference points are preferred because they show significant correlation with age and age-related differences.

Furthermore, based on the ceiling effects in our study, we hypothesize that adapting the TG test by performing 10 consecutive heel-to-toe steps with EC will improve sensitivity and specificity for detecting vestibular or somatosensory problems [31, 32]. This modification may give additional information about the contribution of somatosensory and/or vestibular deficiencies.

Strengths

This study provides novel insights into age-related changes in somatosensation, vestibular function, and balance and how these aspects are interrelated. In addition, this study adds standardization concerning test location for the assessment of TPT and VT. Finally, this research provides information that age, the perception of touch pressure, vibratory perception, and HVOR gain are important to ensure adequate balance performance (with variances explained by 43%-47%).

Limitations

Results after 70 years of age should be interpreted cautiously because of the rather small sample sizes in decades 8 and 9 and the increasingly variable results, which are typical of an older population. Larger samples, especially in decades 8 and 9, could provide more ac-

curate and stronger age-related effects. However, when people age, they suffer from a variety of comorbidities, which makes the variable results relatively normal after the age of 60 [33, 34]. Gender effects were not considered. Previous literature [17, 36, 57] stated that some gender effects could be present; however, detecting gender differences was not the main purpose of this study.

Future Research

It is advised to include bigger samples, especially in the 8th and 9th decade as the population in these age groups is growing fast worldwide. In addition, more research is needed to find a vestibular function measure that better reflects the natural structural degeneration of the vestibular system.

CONCLUSION

It is often difficult to discriminate pathophysiological from physiological aging. The goals of this study were primarily to evaluate the impact of the physiological aging process on somatosensory, vestibular, and balance functions and second, to examine the extent to which age, somatosensory, and vestibular functions can predict balance performance. Dynamic balance, standing balance, TPT, and VTs show age-related changes. The deterioration of these variables starts at around decade 6 but becomes more significant after the age of 60 years. However, the group older than 50 years is a heterogeneous group, showing variable results. Balance outcomes are explained by age and somatosensory variables, but the TG performance was also influenced by the HVOR gain. Therefore, it is recommended to use all complementary tests to distinguish between physiological and pathological aging.

Ethics Committee Approval: This study was approved by Human Research Ethics Committee of the University Hospital of Antwerp (UZA) and the University of Antwerp (UA) and has the following Belgian registration number: B300201836268

Informed Consent: Written informed consent was obtained from the patients who participated in this study.

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Appendix Table 1. Division of the Semmes-Weinstein monofilaments (20-piece) with corresponding size and target force

Filament number	Filament	Evaluator size	Target force (g)	Target force (mN)
1	A	1.65	0.008	0.078
2	B	2.36	0.02	0.196
3	C	2.44	0.04	0.392
4	D	2.83	0.07	0.686
5	E	3.22	0.16	1.569
6	F	3.61	0.4	3.922
7	G	3.84	0.6	5.882
8	H	4.08	1.0	9.804
9	I	4.17	1.4	13.725
10	J	4.31	2	19.608
11	K	4.56	4	39.216
12	L	4.74	6	58.824
13	M	4.93	8	78.431
14	N	5.07	10	98.039
15	O	5.18	15	147.059
16	P	5.46	26	254.902
17	Q	5.88	60	588.235
18	R	6.10	100	980.932
19	S	6.45	180	1764.706
20	T	6.65	300	2941.176

g: grams; mN: millinewton

Appendix Table 2. Touch pressure threshold: levels of significance between each decade

	DP1	MT1	MT5	Heel	Instep	IS
3 vs. 5				0.02*		
3 vs. 6	0.04*	<0.01**	<0.01**	<0.01**		0.02*
3 vs. 7	0.04*	0.04*	<0.01**	<0.01**		
3 vs. 8		0.02*	<0.01**	0.02*	<0.01**	<0.01**
3 vs. 9	0.02*	0.02*	<0.01**	0.02*		<0.01**
4 vs. 6				0.02*		
4 vs. 9			0.04*	0.02*		
6 vs. 8						0.04*
6 vs. 9						0.02*

Significance is determined by Mann-Whitney U post hoc test with Bonferroni-correction; only values who are significant are represented in this table.
*p<0.05; **p<0.01; DP1: first distal phalanx; MT1: head of first metatarsal; MT5: head of fifth metatarsal; IS: interosseal space between heads of first and second metatarsals

Appendix Table 3. Vibration threshold: levels of significance between each decade

	NT				RSTF		
	TT	MM	MT1		TT	MM	MT1
3 vs. 6	<0.01**	<0.01**	<0.01**	3 vs. 6			
3 vs. 7	<0.01**	<0.01**	<0.01**	3 vs. 7	0.02*	<0.01**	0.02*
3 vs. 8	0.02*	<0.01**	<0.01**	3 vs. 8		<0.01**	0.02*
3 vs. 9	0.02*	<0.01**	<0.01**	3 vs. 9		<0.01**	
4 vs. 6			<0.01**	4 vs. 6			
4 vs. 7		0.04*	<0.01**	4 vs. 7			
4 vs. 8		<0.01**	<0.01**	4 vs. 8			
4 vs. 9		<0.01**	<0.01**	4 vs. 9			
5 vs. 7	0.04*			5 vs. 7			
5 vs. 8	0.02*	<0.01**	<0.01**	5 vs. 8			
5 vs. 9	0.04*	0.02*	0.02*	5 vs. 9			
6 vs. 7				6 vs. 7	<0.01**	<0.01**	
6 vs. 8		<0.01**	<0.01**	6 vs. 8		0.02*	0.04*
6 vs. 9	0.02*	<0.01**	<0.01**	6 vs. 9		0.02*	

Significance is determined by Mann-Whitney U post hoc test with Bonferroni-correction; only values who are significant are represented in this table.
*p<0.05; ** p<0.01; NT: neurothesiometer; RSTF: Rydel-Seiffer tuning fork; TT: tuberositas tibiae; MM: malleolus medialis; MT1: head of metatarsal 1.

Appendix Table 4. Standing balance: levels of significance between each decade

	SOFec	TReo	TRec	SLSeo	SLSec	SBS
3 vs. 6					<0.01**	<0.01**
3 vs. 7			0.04*		<0.01**	<0.01**
3 vs. 8			<0.01**	<0.01**	<0.01**	<0.01**
3 vs. 9	<0.01**		<0.01**	<0.01**	<0.01**	<0.01**
4 vs. 7					<0.01**	<0.01**
4 vs. 8			<0.01**		<0.01**	<0.01**
4 vs. 9				<0.01**	<0.01**	<0.01**
5 vs. 7					<0.01**	<0.01**
5 vs. 8			<0.01**	0.04*	<0.01**	<0.01**
5 vs. 9			0.02*	<0.01**	<0.01**	<0.01**
6 vs. 7				0.02*	<0.01**	<0.01**
6 vs. 8			<0.01**	<0.01**	<0.01**	<0.01**
6 vs. 9	<0.01**	0.04*	<0.01**	<0.01**	<0.01**	<0.01**
7 vs. 9				0.04*		

Significance is determined by Mann-Whitney U post hoc test with Bonferroni-correction; only values who are significant are represented in this table.
*p<0.05; **p<0.01; ROM: Romberg; SOF: stand on foam; TR: tandem Romberg; SLS: single leg stance; EO: eyes open; EC: eyes closed; SUMbal: sum of all standing balance tests

Appendix Table 5. Dynamic balance: levels of significance between each decade

	TUG	Tandem gait
3 vs. 6	<0.01**	
3 vs. 7	<0.01**	
3 vs. 8	<0.01**	<0.01**
3 vs. 9	<0.01**	<0.01**
4 vs. 6	0.04*	
4 vs. 7	<0.01**	
4 vs. 8	<0.01**	
4 vs. 9	<0.01**	<0.01**
5 vs. 8	<0.01**	
5 vs. 9	<0.01**	<0.01**
6 vs. 8	<0.01**	<0.01**
6 vs. 9	<0.01**	<0.01**
7 vs. 8	<0.01**	
7 vs. 9	<0.01**	<0.01**

Significance is determined by Mann-Whitney U post hoc test with Bonferroni correction; only values who are significant are represented in this table.
*p<0.05; **p<0.01; TUG: Timed Up and Go