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SYSTEMATIC REVIEW

A Systematic Review of the Relationship between Physical Activities in Sports or Daily Life and Postural Sway in Upright Stance

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Abstract
Background In many sports, maintaining balance is necessary to compete at a high level. Also, in many health problems, balance is impaired. Postural sway (PS) is often used as an indicator of upright balance control, and physical activity (PA) might enhance balance control. However, the relationship between PS and PA has never been systematically reviewed.
Objective Our objective was to summarize the evidence regarding the relationship between PS in upright bipedal and unipedal standing and PA.
Methods We conducted a literature search in MEDLINE, EmBase, CINAHL, the Cochrane Database, and PEDro, up to March 2012, with no limit on the starting date. Characteristics and methodological aspects of each article were extracted by two reviewers. We used centre of pressure (CoP) velocity, and variables related to the CoP area, to compare studies.
Results A total of 39 articles were reviewed from an initial yield of 2,058. Of these 39 studies, 37 used a comparative design, one was a cohort study, and one was a randomized controlled trial.
Conclusion The main conclusion was that in general, sport practitioners sway less than controls, and high-level athletes sway less than low-level athletes. Additionally, we identified specific effects dependent on the use of vision, sport-specific postures, and frequency and duration of the (sports) activity. PS in unperturbed bipedal stance appears to have limited sensitivity to detect subtle differences between groups of healthy people.

1 Introduction

Postural sway (PS) is the pattern created by the process of continuous small body deviations from an upright body position countered by corrective torques [1]. It can be studied by recording the movement of the centre of pressure (CoP). Many health problems, such as low back pain [2], anterior cruciate ligament ruptures [3–5], ankle injury [6, 7], stroke [8, 9], diabetic neuropathy [10, 11], and Parkinson's disease [11], are associated with an increase in PS. Several studies have also shown an increase in PS with aging [12–14]. It is generally thought that more spontaneous PS in unperturbed stance is a result of impaired balance control. Optimizing balance control may benefit physical rehabilitation for health problems and the deteriorating effect of age.

In a recent review, Hrysomallis studied whether PS is a determinant of sports performance. Based on cross-sectional studies, he concluded that balance ability is related to competition level for some sports, and to a number of

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performance measures [15]. In designing rehabilitation interventions, the opposite question is of interest: does performing physical (sport) activities lead to improved balance control? Since studies reviewed by Hrysomallis were cross-sectional, the direction of causality, if any, is unclear, but the overall conclusion may suggest a positive answer. Indeed, numerous studies have found an association between physical activity (PA) and balance control, as measured by PS [7, 16–43]. However, the data are inconclusive regarding direction and strength of the association. The fact that the work by Hrysomallis was not designed as a systematic review precludes a more definitive answer. Also, it is not clear which elements of PA are associated with a reduction in PS. Answering this question could prove useful in designing optimal interventions for balance control.

One possibility is that these elements of PA consist of a general transfer of training balancing activities to balance control and hence PS; for example, there are indications that higher levels of PA could lead to a decrease in PS in the elderly [44, 45]. On the other hand, it is possible that balance abilities are specific to a particular task, a principle known as Henry's hypothesis [46]. In this case, it is of interest which elements characterize the sports with the strongest association with PS.

Taking all these uncertainties into account, we formulated the following questions as the objective of this review: "is PA associated with a decrease in PS in unipedal or bipedal stance?" and "is practicing a sport that specifically challenges balance associated with a decrease in PS in unipedal or bipedal stance?".

2 Methods

We conducted a literature search in MEDLINE, EmBase, CINAHL, the Cochrane Database, and PEDro up to 3 March 2012. The following search string was used for the electronic databases: ('centre of pressure' [All Fields] OR 'center of pressure' [All Fields] OR 'CoP' [text word] OR 'center of foot pressure' [All Fields] OR 'postural sway' [All Fields] OR 'force plate') AND ('Motor Activity' [Mesh] OR 'Leisure Activities' [Mesh] OR 'Human Activities' [Mesh] OR 'Activities of Daily Living' [Mesh] OR 'sports'). To exclude studies not focusing on healthy populations, the following conditions were attached to the strategy: 'NOT ('Stroke' [Mesh] OR 'Parkinson Disease, Secondary' [Mesh] OR 'Parkinson Disease' [Mesh] OR 'Multiple Sclerosis' [Mesh])'. The search strategy was adapted to each database. Two researchers (HK and HD) independently screened search results for potentially eligible studies. When titles and abstracts suggested that a study was potentially eligible for inclusion, a full text copy of the paper was obtained. In addition, all references of eligible papers were screened for relevant studies. Disagreement between researchers was resolved by discussion. Table 1 shows the criteria used for inclusion and exclusion. Data of the characteristics of the study were independently extracted by HK and HD.

We included both cross-sectional and longitudinal studies. Since there is no consensus on a reliable and valid instrument to assess the methodological quality of cross-sectional studies [47, 48], neither rating nor weighing of studies was performed. However, we extracted aspects of methodological quality from the reports and incorporated them in our interpretation of the results. The appraised variables were as follows: comparability of studied groups on sex [49], age [50, 51], body height [49], body weight [49, 50], and foot length [49]. Furthermore, we looked at group size, because of the potential lack of power in small sample sizes.

We only searched for studies that used variables that describe the movement of the CoP. Variables that were related to a static position, e.g., the mean CoP position or a change in the mean CoP position movement, were not analysed. Variables in the category 'other' were registered but not analysed. When no direct comparison was made between groups of interest by the authors of the articles, the available data (e.g., mean and standard deviation) were used to test whether differences were statistically significant.

3 Results

The search strategy yielded 2,058 articles. Figure 1 is a flow diagram showing information about the number of studies identified, included and excluded studies, and reasons for exclusion. Based on titles and abstracts, 35 full-text copies of the papers were obtained. Seven studies were excluded after reading full texts. Screening the references of the 28 articles that remained identified 22 additional and potentially relevant titles, of which six were included. Finally, a search of all publications of first authors was conducted, after which a total of 39 articles were included. The characteristics and aspects of methodological quality of the included studies are presented in Table 2, group comparisons and detailed results in Table 3. PS was measured under different circumstances, analyzed in different directions, and quantified using a wide range of dependent variables. Therefore, in addition to the detailed results in Table 3, a summary of the main results is presented in Tables 4 and 5. In these tables, results are summarized as a positive, a negative, or no significant association. Table 4 describes comparisons of sport practitioners with control groups with no specific PAs, or practitioners of the same or other sports at a lower level. In the following sections,

Table 1 Inclusion and exclusion criteria

Inclusion	Exclusion
• Studies concerning healthy adults (18–65 years)	• Single case reports
• Studies that assess postural sway by centre of pressure area or velocity measurements in bipedal or unipedal stance without perturbations	• Experiments with therapeutic interventions aimed to improve postural control
• Studies that compare groups that participate in different sports, or differ in level of activity	• Measurements on a moveable or non-firm surface
• Studies published in English, German, French or Dutch	
• Publications up to March 2012	

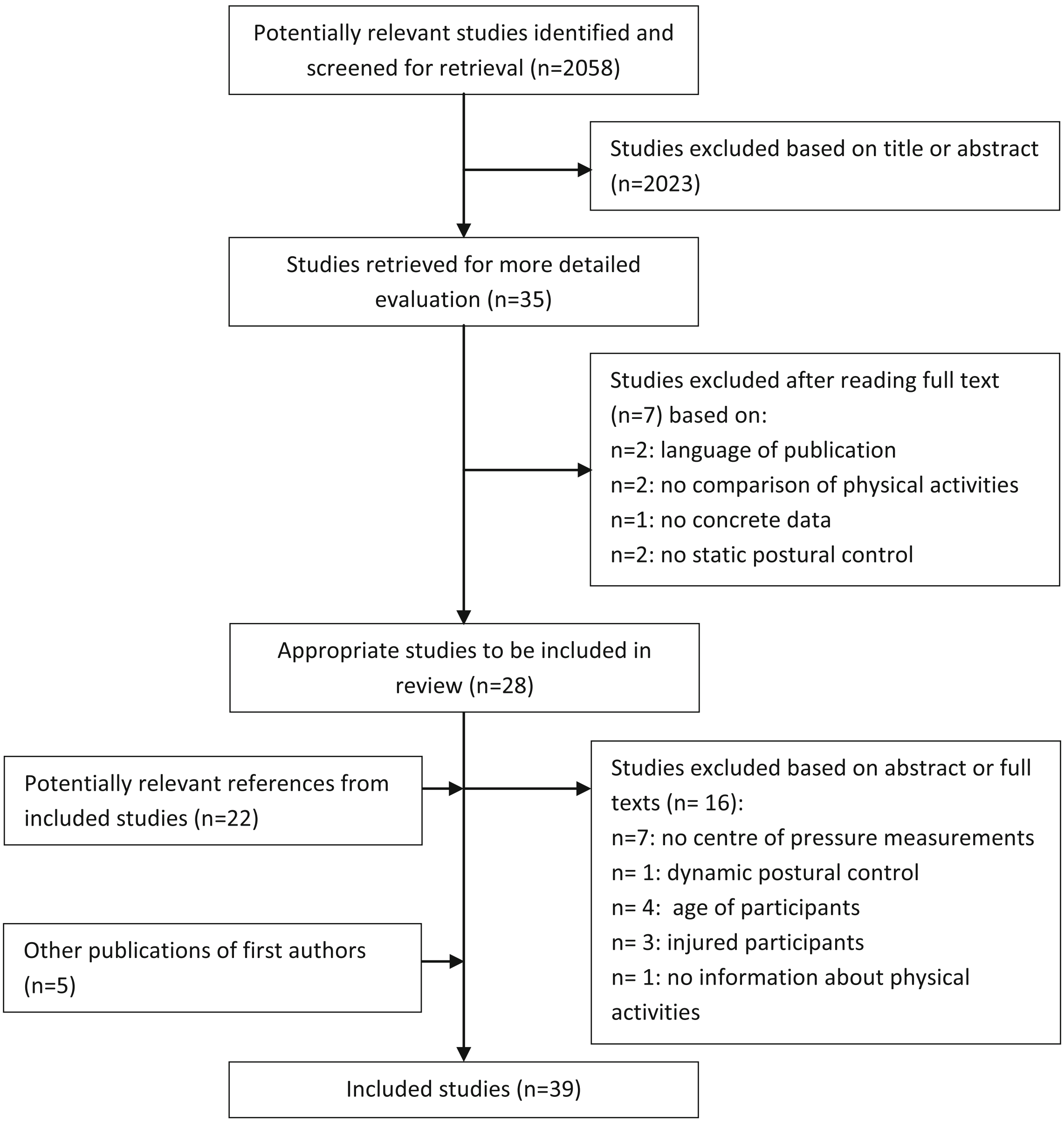

Fig. 1 Flow chart of publication selection. *n* number of studies

these will be referred to as ‘controls’. Table 5 describes comparisons with sport practitioners of similar levels from a different sport.

All included studies were cross-sectional studies and had a comparative design except the studies of Ageberg et al. [12], which used a regression analysis within a cohort,

Table 2 Study characteristics and aspects of methodological quality

Sport/activity	Author and year	Position	Trial	Task	Visual instructions	Sex	Age	Weight/height/foot size	General activity level	Sample size
Basketball	Leanderson et al. [52]	Foot in contact with other foot, arms close to chest	60 s preceded by an anticipation period of 15–30 s	NR	Focus at a spot on the wall	+	+	+	+	−
Cycling	Lion et al. [40]	NR	20 s, mean of 3 trials	Sway as little as possible	Three-sided surroundings without focus	−	+	+	+	+
Dancing/soccer	Gerbino et al. [22]	Foot raised, in contact with supporting leg. Arms could be used for balance freely	10 s, preceded by 10 s not analyzed. One practice trial. Mean of 3 trials	NR	Looking straight ahead	+	+	Dancers significantly less weight	Dancers trained 2 h more per day	+
Dancing	Hugel et al. [23]	Barefoot, positioning on marks, arms extended, head upright	20 s. One preliminary trial	Asked to maintain a static balance	Looking on a mark on the wall at 2 m	NR in controls	+	NR: likely to be different	Controls without regular PA	+
	Leanderson et al. [7]	Foot raised, in contact with supporting leg, arms held to the chest	60 s recording each foot, 15 s adaptation	NR	Looking at a spot at 4 m	+	+	"Confounding due to body height[b]"	NR	+
Dancing/track athletes	Schmit et al. [33]	Shoulder-width stance, arms hanging naturally and comfortably	30 s. Mean of 4 trials. Start of trial when participant stood stable	Asked to relax	NR	+	+	NR: likely to be different	+	−
	Simmons [34]	Barefoot, arms relaxed by the sides, feet shoulder width	20 s. Mean of 3 trials	NR	Three-sided surroundings without focus	+	+	+	+	+
Football	Handrigan et al. [53]	Feet 10 cm apart, arms alongside the body	30 s. Mean of 4 trials	Attempt to stand as still as possible	Fixing on a reference point on eye level	+	−	BMI in football and obese higher	−	−
General activity	Ageberg et al. [12]	Leg 90° hip and knee, arms hanging	25 s, average of 3 trials preceded by 20 s not analyzed	Stand as motionless as possible	Looking at a mark on the wall	+	+	+	Variable of interest	+
Gymnastics	Asseman et al. [17]	Arms relaxed, bipedal, width freely chosen. Unipedal: leg fixed under the other knee	34 s. Middle 32 s used for analysis. Mean of 5 trials per condition	Keep as still as possible	Horizontal gaze fixed on a mark at 3 m distance	NR for other sports	+	Gymnasts smaller and lighter	NR	+

Table 2 continued

Sport/activity	Author and year	Position	Trial	Task	Visual instructions	Sex	Age	Weight/height/foot size	General activity level	Sample size
	Gautier et al. [21]	Barefoot, comfortable position	70 s of which first 20 s analyzed	NR	Dark room, looking at a flat projection screen	+	+	+	+	+
	Vuillerme et al. [36]	Barefoot, feet together, hands hanging loosely	20 s of which the first 5s analyzed. Average of 8 trials	Remain as immobile as possible	Fixate at white cross at 1.20 m. EC: gaze straight-ahead	+	+	+	+	−
	Vuillerme et al. [37]	Barefoot, straight, arms hanging loosely, positioning as in Vuillerme and Nougier [38]	10 s	Immobile as possible	Fixate at white cross at 1.20 m	+	+	+	+	−
	Vuillerme and Nougier [38]	Barefoot, feet 20°, heels 4 cm apart. Unipedal: big toe of other foot touching medial ankle	20 s	Sway as little as possible	Fixate at white cross at 1.20 m	+	+	+	+	−
Golf	Stemm et al. [54]	NR	10 s	NR	NR	+	+	+	NR	+
Ironman	Nagy et al. [28]	Barefoot, feet side by side, no space in between	20 s, of which the last 16 used for analysis	Minimize PS	Looking at a mark on the wall	+	+	+	Variable of interest	−
Judo	Paillard et al. [55]	Bipedal, arms hanging, legs straight	51.2 s	Stand as still as possible	NR	+	+	+	+	−
Judo/dancing	Perrin et al. [32]	Feet 10 cm apart, arms along the body, barefoot	20 s	NR	Stare straight ahead at a dot on eye level 2 m away	F dancers, M judo, control mixed	+	NR	Control group lower level	+
Rhythmic gymnastics	Calavalle et al. [18]	Barefoot, arms hanging freely at the side, feet 30° angle, heels 3 cm apart	60 s	Stand as immobile as possible	Focus on eye-level target	+	RG 4 year younger vs. controls	Height and weight less in RG	NR	+
Shooting	Aalto et al. [16]	Heels together, feet 30°, knees locked, arms crossed over the chest	90 s (30–57 s and 60–87 s used for analysis)	NR	NR	NR in controls	+	NR	NR	−
	Era et al. [20]	Shooting, top level, wearing competition clothes	7.5 s preceding a shot, analyzed in 5 intervals of 1.5 s	Aiming	Aiming	+	+	Top level higher weight[a]	+	−

Table 2 continued

Sport/ activity	Author and year	Position	Trial	Task	Visual instructions	Sex	Age	Weight/height/ foot size	General activity level	Sample size
Shooting/ fencing	Herpin et al. [43]	Barefoot, arms at the sides	20 s	Remain as stable as possible	Look straight ahead at a dot on eye level 2 m away	+	+	+	Controls were sedentary	+
	Konttinen et al. [24]	Shooting position, with shooting and competition clothes	1 trial of 6 s preceding the shot. Data analyzed in intervals of 1.5 s	Aiming	Aiming	+	+	+	NR	–
	Larue et al. [25]	Shooting position, with shooting and competition clothes	6 s	Aiming	Aiming	NR	+	NR	NR	–
	Niinimaa and McAvoy [29]	Shooting position	60 s	Aiming	Aiming	+	Athletes ± 12 years older vs. controls	+	NR	–
	Su et al. [35]	Comfortable and narrow stance	15 s	Aiming	Aiming	+	+	+	NR	+
Skiing	Noé and Paillard [42]	Knees extended	51.2 s	Remain as still as possible	NR	+	+	+	National/ regional level 25/ 12 h p/w training	–
Soccer	Jakobsen et al. [56]	Elevated leg at least 5 cm above platform, hands at hip	2 trials of 30 s each leg. Trial with shortest path length per leg was averaged with other leg	NR	Looking at a fixed target, 1.65 m high, 2.5 m away	+	+	+	+	–
	Matsuda et al. [27]	Hands on hips, hip 20° flexed	3 trials of 60 s each leg	NR	NR	+	+	+	NR	–
	Matsuda et al. [57]	Bipedal: heels together, arms hanging loose. Unipedal: hands on hips, hip 20° flexed	3 trials of 60 s each leg. Mean of the two with lowest sway was used for analysis	NR	Looking at a fixed point	+	+	+	–	+
	Paillard et al. [30]	Arms along the body, foot on landmarks, leg flexed at 90° at the knee	51.2 s	Stand as still as possible	Looking at a mark on the wall	+	+	+	–	+

Table 2 continued

Sport/ activity	Author and year	Position	Trial	Task	Visual instructions	Sex	Age	Weight/height/ foot size	General activity level	Sample size
	Paillard and Noé [31]	Arms along the body, feet on landmarks, legs straight, feet 30°. 5 cm apart	51.2 s	Stand as still as possible	Looking at a mark on the wall	+	+	+	NR	+
	Paillard et al. [58]	Barefoot, arms along the body, feet on landmarks, legs straight, feet 30°. 5 cm apart	51.2 s	Stand as still as possible	Looking at a fixed target, 2 m away	+	+	+	National/ regional level 5/6 vs. 2 days p/w training	−
Surfing	Chapman et al. [19]	Foot position was standardized	30 s	Attempt to stand as still as possible	Gazing in a 'natural forward direction at nothing in particular' at a blank, white wall	+	+	Expert surfers smaller and lighter than swimmers	+ (expert surfers > swimmers)	+
	Paillard et al. [41]	Barefoot, arms along the body, feet together, legs straight	50 s	Stand as still as possible	Looking at a fixed target, 2 m away	+	+	+	NR	−
Taekwondo	Leong et al. [59]	Barefoot	20 s. Mean of 3 trials	Attempt to stand as still as possible	Looking forward	+	−	+	−	+
Tai Chi	Guan and Koceja [60]	NR	3 trials of 15 s	NR	NR	+	+	+	+	+
	Mak and Ng [26]	Arms hanging freely	10 s	NR	Looking at a target	NR	+	NR	NR	−
	Wu et al. [39]	Heels 10 cm apart, toes 10°	30 s. Average of 5 trials	Stand as stable as possible	Looking at a mark on the wall	+	+	+	+	+

BMI body mass index, *EC* eyes closed, *F* female, *M* male, *NR* not reported, *PA* physical activity, *PS* postural sway, *p/w* per week, *RG* rhythmic gymnasts

+ no significant differences between groups, or analysis adjusted for this characteristic. Sample size >10 in each group

− significant difference between groups and no adjustment in the analysis. Sample size in 1 or more groups 10

[a] Top-level shooters higher weight due to wearing competition clothes. No differences in height

[b] Height and weight not reported

Table 3 Group comparisons and detailed results

Sport/activity	Author and year	Sport practitioners (number, sex, level, age) mean ± SD or range	Controls (number, sex, activity, level, age) mean ± SD or range	Eyes open bipedal	Eyes open unipedal	Eyes closed bipedal[a]	Eyes closed Unipedal[a]	Author's conclusions[b]
Basketball	Leanderson et al. [52]	13 ankles of 9 M players, 2nd division league, 24 (20–29)	11 controls, M, 25.5 (20–29), normally active		A, A_{dx}, A_{dy}			None
Cycling	Lion et al. [40]	20 M, 4 F, off-road cyclists, all levels, IQR 20.5 ± 6.9	24 M, road cyclist, all levels, IQR 22.1 ± 8.8	**A%⤒**		A% ⤒		Road cyclists have a preferential usage of visual information
Dancing/ soccer	Gerbino et al. [22]	32 F modern and classical dance first level, 20.3 ± 1.5	32 F soccer players, varsity, age 19.7		**A ⤓**, V ⤓		A, V ⤓	Dancers have better standing balance than soccer players in some tests
Dancing	Hugel et al. [23]	12 F, 6 M, professional dancers of the National Ballet, 16–37	46, sex NR, healthy, never regularly practiced any PA	**A ⤓** V ⤒		**V ⤒** A ⤓		Balancing skills cannot be transferred to tasks of everyday life
	Leanderson et al. [7]	26 M, 27 F, Royal Swedish Ballet, 26	23 active M and F (20–29)		**A, A_d (M) ⤓**, A (F)			None
Dancing/track athletes	Schmit et al. [33]	5 F, 5 M, student dancers, ≥5 years training, 20	10 track athletes, 5 M, 19.5	V, A_{sd} (x, y)		V, A_{sd} (x, y)		Dancers exhibit different dynamic patterns of PS
	Simmons [34]	17 F, intermediate, advanced or professional, 21.4 ± 0.68	17 matched non-dancers, 21.6 ± 0.39	A%		A%		No differences between groups in static measurements
Football	Handrigan et al. [53]	9 M, 23.4 ± 1.3	17 M obese subjects 36.9 ± 7.73; 15 M controls, 38.5 ± 9.7, both groups no regular PA	Football vs. C; **V, Range x, Range y ⤒** Football vs. obese; V, range y ⤓ Range x		Football vs. C; **V ⤒** Football vs. obese; V ⤓		None
General activity	Ageberg et al. [12]	36 M, 39 F healthy volunteers, 29.5 ± 8.2	Regression analysis		In M; V_x, V_y, A_x ⤓ A_y ⤒ In F; A_x ⤓ V_x V_y A_y ⤒			Activity level did not significantly affect standing balance
Gymnastics	Asseman et al. [17]	13 M elite, 21.6 ± 4	13 other sportsmen regional level 22.1 ± 3	V, A ⤒	A ⤓, V ⤓	V, A ⤒	V, A ⤓	Gymnasts only show less sway in trained configurations
	Gautier et al. [21]	12 M, nationally ranked 22.2 ± 4.1	12 M non-gymnasts experts in other sports, 21.7 ± 3.1	A_{sdy} ⤒				None
	Vuillerme et al. [36]	7 M, >10 years regional or higher, 21.1 ± 1.3	7 M soccer and handball, experts, 22.6 ± 2.1	V_y		V_y		None
	Vuillerme et al. [37]	6 M experts, 20.6 ± 1.4	6 M soccer, handball tennis, experts, 23.3 ± 1.5	V, Range	Range ⤒, V	Range ⤒, V	**V, Range ⤓**	EO no differences. Gymnasts less sway during EC unipedal
	Vuillerme and Nougier [38]	7 M experts, regional or higher, 20.1 ± 2.0	7 M soccer and handball. Experts, 22.0 ± 3.6	V	V ⤓			Gymnasts are less dependent on cognition for postural control
Golf	Stemm et al. [54]	17 M, handicap 0–9, mean age all groups (including controls) 39.6	16 M golfers, handicap 10–16, 19 M golfers, handicap 17+	V	V			Balance is not significantly different among golfers with different skills

Table 3 continued

Sport/activity	Author and year	Sport practitioners (number, sex, level, age) mean ± SD or range	Controls (number, sex, activity, level, age) mean ± SD or range	Eyes open bipedal	Eyes open unipedal	Eyes closed bipedal[a]	Eyes closed Unipedal[a]	Author's conclusions[b]
Ironman	Nagy et al. [28]	10, 33 ± 7.6	10 firemen, active in sports, 3 times p/w, 33 ± 4.1	V, V_x $\downarrow$ V_y		$\boldsymbol{V}$, $\boldsymbol{V_x}$, $\boldsymbol{V_y}$ $\downarrow$		Ironman are more stable and less dependent on vision for postural control than the control subjects
Judo	Paillard et al. [55]	11 M 17.6 ± 0.3, (inter) national level	9 M regional level, 17.4 ± 0.4	V, V_x, V_y, V_{sd}, A $\downarrow$		V, V_x, V_y, V_{sd}, A $\uparrow$		No differences. Vision is more important to higher level judoists
Judo/dancing	Perrin et al. [32]	17 M, judoist (inter)national, 24.8 ± 4.5. 14 F, dancers national ballet, 22.1 ± 4.5	21 F, 21 M, low level of PA, 23.9 ± 4.2	Judo vs. C; $\boldsymbol{V}$ **&** $\boldsymbol{A/s}$ $\downarrow$ V_y $\downarrow$ V_x $\uparrow$ Judo vs. dancers; V, V_y, A/s $\downarrow$ V_x $\uparrow$ Dancers vs. C; V, V_y, A $\downarrow$ V_x		Judo vs. C; $\boldsymbol{V}$ **&** $\boldsymbol{A/s}$ $\downarrow$, V_y $\downarrow$ V_x Judo vs. dancers; $\boldsymbol{V_x}$, $\boldsymbol{A/s}$ $\downarrow$, V_y $\downarrow$ Dancers vs. C; V_y $\downarrow$, V, A $\uparrow$ $\boldsymbol{V_x}$ $\uparrow$		Judoists do better in all circumstances. Visual input is of major importance in dancers
Rhythmic gymnastics	Calavalle et al. [18]	15 F, 18.4 ± 4.6, experts	43 sports students, F no experts, 22.1 ± 5.6	$\boldsymbol{A_{dx}}$ $\downarrow$ A $\downarrow$ A_d $\downarrow$ $\boldsymbol{A_{dy}}$$\uparrow$		$\boldsymbol{A_{dx}}$ $\downarrow$ A $\downarrow$ A_d $\downarrow$ $\boldsymbol{A_{dy}}$$\uparrow$		Rhythmic gymnastics seems to have a direct effect on the ability to maintain bipedal posture, especially in ML direction
Shooting (including biathlon)	Aalto et al. [16]	8 rifle, 2 pistol shooters, 2 F, 8 M, national team, 33.1 (17–51)	27 soldiers, 34.1 (19–57)	$\boldsymbol{V}$$\downarrow$		$\boldsymbol{V}$$\downarrow$		Training improves posture
	Era et al. [20]	6 M, 31.8 ± 7.5; 3 F, 28.7 ± 5.1, international; 8 M, national, 28.3 ± 4.8	7 M, basic knowledge of shooting, 31.6 ± 5.3	$\boldsymbol{A}$, $\boldsymbol{V_y}$, $\boldsymbol{V_x}$ $\downarrow$				Systematically better postural control in trained athletes
Shooting/ fencing	Herpin et al. [43]	4 F, 6 M, shooters, national level, IQR 19.5 ± 2.8; 5 F, 7 M, fencers, national level, IQR 22 ± 2.2	3 F, 7 M, no sporting activities, IQR 23 ± 1.3	Shooters and fencers vs. C: V, A $\downarrow$, A_y $\uparrow$ $\boldsymbol{A_x}$ $\downarrow$ Shooters vs. fencers V, A_x, A_y, A $\downarrow$		Shooters and fencers vs. C: $\boldsymbol{V}$, $\boldsymbol{A}$, $\boldsymbol{A_x}$ $\downarrow$ A_y $\downarrow$ (fencers vs. C A_y); Shooters vs. fencers V, A, A_y, A_x $\downarrow$		Balance control was more efficient in fencers and shooters
	Konttinen et al. [24]	6 rifle shooters, M, international level, 31.8 ± 7.5	6 rifle shooters, M, national, 30.2 ± 3.5	$\boldsymbol{V_x}$, $\boldsymbol{V_y}$, **Aside** $\downarrow$				Elite shooters sway less than non-elite, main difference in V_y
	Larue et al. [25]	2 rifle shooters, M, expert, 23; 2 M biathlon expert, 32.5	2 M biathlon novice, 25.5; 2 rifle shooters, M, novice 23.5	$\boldsymbol{V}$, $\boldsymbol{V_{sd}}$ $\downarrow$				Biathletes and rifle shooters adapt to the specific demands of their discipline
	Niinimaa and McAvoy [29]	4 M rookies, 20.5 ± 2.1; 4 biathletes M, 30 ± 4; 4 shooters M, 35 ± 17.5	4 M, 21 ± 0.8	$\boldsymbol{V_x}$ $\downarrow$; V, V_y $\downarrow$				None
	Su et al. [35]	6 M rifle shooters, 21.2 (17–30); 5 F, 16.8 (16–18). Olympic level	11 M, 25.3 (24–28), 11 F 22 (21–23), college students	$\boldsymbol{V}$, $\boldsymbol{V_{max}}$ $\downarrow$ A		$\boldsymbol{V}$, $\boldsymbol{V_{max}}$ $\downarrow$ A $\downarrow$		Shooters have better stability than untrained controls
Skiing	Noé and Paillard [42]	7 M, national level, 22 ± 3	7 M, regional level, 18 ± 1	$\boldsymbol{A}$$\uparrow$ V $\uparrow$		$\boldsymbol{A}$$\uparrow$ V $\uparrow$		National skiers displayed inferior performance

Table 3 continued

Sport/activity	Author and year	Sport practitioners (number, sex, level, age) mean ± SD or range	Controls (number, sex, activity, level, age) mean ± SD or range	Eyes open bipedal	Eyes open unipedal	Eyes closed bipedal[a]	Eyes closed Unipedal[a]	Author's conclusions[b]
Soccer	Jakobsen et al. [56]	43 M, untrained, 21–45 years, RCT	12 soccer, 12 running, 9 high-intensity interval running, 10 no training		Soccer vs. C; V, A ⤓ Soccer vs. interval, running; V, A ⤓ Interval vs. C: V, A ⤓ Interval vs. Running; V, A ⤓ Running vs. C; V⤓, A ⤓			Soccer, interval, and running reduced sway. Soccer superior changes postural control
	Matsuda et al. [27]	10 M soccer, 20.8 ± 2.5; 10 M basketball 19.6 ± 0.5; 10 M swimming 20.1 ± 1.3. All >6 years training	10 non athletes, M, 20.9 ± 0.9		[c]Soccer vs. all; A_x, A_y ⤓ Soccer vs. swimming and C; V ⤓ Soccer vs. basketball; V Basketball vs. C; V Basketball vs. swimming; A_y ⤓ Basketball vs. swimming and C; A_x ⤒			Soccer players have superior balance in unipedal stance
	Matsuda et al. [57]	25 M, regional level 20.5 ± 2	25 no soccer players, M 21.2 ± 1.3	[c]**V**, A_x, A_y ⤓	[c]**V**, A_x, A_y ⤓			None
	Paillard et al. [30]	15 M, national, 24 ± 3	15 M soccer players, regional, 23 ± 3		V, A ⤓		V, A ⤓	In soccer-specific test conditions, sports level influenced performance
	Paillard and Noé [31]	15 M, national level, 24 ± 3	15 M, regional level, 23 ± 3	V, V_{sd}, A ⤓		V, V_{sd}, A ⤓		Intense training allows PRO soccer players to become less dependent on vision
	Paillard et al. [58]	8 M, national level, 24 ± 3	9 M, regional level, 23 ± 2	V ⤓, A		V ⤓, A		National level showed better postural control
Surfing	Chapman et al. [19]	21 M, expert surfers, 24.4 ± 4	20 M surfers, recreational (C), 24.2 ± 3; 19 M swimmers and water polo experts, 21.5 ± 2	Surfers vs. swimmers; V ⤒, A ⤒ Surfers vs. C; V, A ⤒		Surfers vs. swimmers; A ⤓ V ⤒ Surfers vs. C; V, A ⤒		Standard sway indices are not able to differentiate between surfers and controls
	Paillard et al. [41]	9 M, (inter) national level, 22.1 ± 3.1	8 M, local level, 22.2 ± 3.3	V ⤓, A ⤓		V ⤓, A ⤓		(Inter) national-level surfers did not have better postural control
Taekwondo	Leong et al. [59]	5 M, 6 F, <4 h/week training, 20.9 ± 1.5	7 M, 4 F controls, no regular training, 24 ± 3.8	A% ⤓		**A%** ⤓		Taekwondo practitioners have better balance, especially in EC
Tai Chi	Guan and Koceja [60]	8, sex NR, 3 days p/w >1 h for >3 years, 44 ± 12	8 non Tai Chi practising, 43 ± 11.5	A ⤓		A ⤓		Tai Chi practitioners demonstrated improved postural control
	Mak and Ng [26]	16 F, 3 M, 61.9 ± 4.8, 30–45 min >3 × p/w >1 year	4 M, 15 F, physically active, 63.4 ± 4.4	A_y ⤓ V, A, A_x ⤓	V, A, A_x, A_y ⤓	A, A_y ⤓ V, A_x ⤓		Tai Chi practitioners have better balance

Table 3 continued

Sport/activity	Author and year	Sport practitioners (number, sex, level, age) mean ± SD or range	Controls (number, sex, activity, level, age) mean ± SD or range	Eyes open bipedal	Eyes open unipedal	Eyes closed bipedal[a]	Eyes closed Unipedal[a]	Author's conclusions[b]
	Wu et al. [39]	10 M, 10 F, 62 ± 4 3 days p/w 1 h for >3 years	5 M, 14 F, PA level equal, 63 ± 4	**Range x, Range y** ↓		**Range x, Range y** ↓		None

↓ = lower velocity or smaller area, no arrow = same velocity or area, or no effect size reported, ↑ higher velocity or more area; significant ($p < 0.05$) outcomes are in bold

A area (i.e. 1 SD mean CoP, 90 % confidence ellipse), A_d mean amplitude, A_{sd} SD of CoP position, *A/s* area per second, *Aside* length of the side of the CoP square, *A%* percentage mean amplitude (AP) of theoretical maximum, *C* controls (no specific sports, or lower level of sport), *CoP* centre of pressure, *EC* eyes closed or vision occluded, *EO* eyes open, *F* female, *IQR* median and interquartile range, *M* male, *ML* medio-lateral, *NR* not reported, *PA* physical activity, *PS* postural sway, *p/w* per week, *Range* maximal deviation of the CoP position, *RCT* randomized controlled trial, *SD* standard deviation, *V* velocity, V_{max} maximum velocity, V_{sd} SD of Velocity, *x* medio-lateral direction, *y* anterior posterior direction

[a] EC or vision occluded

[b] Only concerning the aim of this review

[c] Variables derived from factor analysis, most prominently resembling velocity and amplitude

and Jakobsen et al. [56], which was designed as a randomized controlled trial (RCT). All but one study examined the effects of various sports activities on PS.

One study used soldiers [16], and another study [28] used fire-fighters as controls; 11studies [7, 23, 26, 34, 35, 39, 52, 53, 57, 59, 60] used controls who did not practice any specific sport, nine used participants of other sports as a control group [17, 18, 21, 22, 33, 36–38, 40], and 12 studies used subjects who participated in the same sports but at a different level from controls [20, 24, 25, 30, 31, 41, 42, 54, 55, 58]. Six studies had two or more control groups. These groups consisted of participants practicing other sports and non-sport practitioners [27, 43, 56], sport practitioners practising the same sport but at another level, controls not participating in any sport [29, 32], practitioners of the same sport but at a different level, and a group practicing another sport [19].

Bipedal stance with eyes open was the most common condition, used in 32 studies [16–21, 23–25, 28–43, 53–55, 57–60]. Bipedal stance with eyes closed was used in 25 studies [16–19, 23, 26, 28, 30–37, 39–43, 53, 55, 58–60]. Unipedal stance with eyes open was used in 13 studies [7, 12, 17, 22, 26, 27, 30, 37, 38, 52, 54, 56, 57], in four of which the participants also had to close their eyes in unipedal stance [17, 22, 30, 37]. Four studies measured PS during a shooting task [20, 24, 25, 29].

3.1 Outcome Variables

Velocity-related (31 studies) and area-related (32 studies) variables were used to a similar extent. Six studies [18, 27, 28, 30, 55, 58] computed Fourier transformations to examine sway in various frequency bands. Three of these six studies, all conducted by the same researcher, used the same frequency bands [30, 55, 58]. Other researchers differed in their choice of frequency bands. One study [33] examined sway dynamics by recurrence quantification analysis (RQA).

3.2 Methodological Aspects

Fourteen studies did not report any data about weight or height of the participants [16, 23, 25, 26, 32, 33], or reported a significant difference between control and experimental groups on one or more of these items [7, 17–20, 22, 59]. This was particularly a problem in studies among dancers, in which only one of five studies [34] reported that differences in anthropometric and demographic variables were not significant. One study reported a significant difference in weight [22], one study a significant difference in height [7], and the other two [23, 33] did not report on anthropometric variables.

In 24 of the 39 studies in this review, a measurement time shorter than 60 s was used; 18 of these 24 used a measurement time of 30 s or less. Five studies in this review [7, 18, 27, 29, 52] used measurements of 60 s or more, and nine studies [12, 33, 34, 39, 40, 53, 56, 57, 59] used average results from multiple measurements that resulted in a total measurement time of 60 s.

In 20 studies [16, 20, 24, 25, 27–29, 33, 36–38, 41, 42, 52, 53, 55, 56, 58, 60], the sample size of the experimental group was smaller than ten, which increases the risk of a type II error. In ten studies, no level of PA was reported, and another ten studies reported that the level of PA differed significantly between groups.

3.3 Results in Different Physical Sport Activities

3.3.1 Shooters

Shooters consistently had lower sway velocity than controls in the seven studies included in this review. In Niinimaa and McAvoy [29] and Herpin et al. [43], the lower velocity in experienced shooters did not reach statistical difference from that of controls. In both studies, a small sample size was used (respectively, $n = 8$ and $n = 10$). Su et al. [35] found one of eight velocity variables did not significantly differ between groups, but was still lower for shooters.

The same pattern as for sway velocity was seen for area-related variables. Two of four studies found significantly lower values for (more experienced) shooters [20, 24]. All three studies conducted in subjects with closed eyes found lower CoP velocity for shooters than for controls [16, 35, 43], and one [43] of two [35, 43] found a significantly smaller area travelled. In a comparison with fencers, no differences were detected between groups, either with eyes open or eyes closed [43].

Two studies measured velocity and area as a function of time during a shooting task. LaRue et al. [25] found sway to decrease with time to the actual shot for all subjects. Era et al. [20] found the same decrease in sway, but only for shooters. In four of the seven studies, participants were not measured in standard static bipedal stance, but in a stance with the upper body rotated towards a target according to the shooting position.

3.3.2 Soccer

In all five studies that compared soccer players with controls, soccer players showed lower sway velocity and smaller area [27, 30, 31, 57, 58]. These differences were statistically significant in bipedal stance with eyes open [31, 57, 58] or eyes closed [31, 58], and in unipedal stance with eyes open [27, 30, 57] and with eyes closed [30]. There was a minority of non-significant differences in these studies (area in bipedal stance eyes open and closed [58], velocity in unipedal stance [27]), and soccer players did not show more sway than controls for any condition or variable.

In two studies, soccer players were compared with other athletes: basketball players, swimmers [27], and dancers [22]. In unipedal stance with eyes open, soccer players showed a smaller sway area than basketball players [27] and swimmers [27], but a larger sway area than dancers [22]. Differences in sway velocity were not significant in these studies. In unipedal stance with eyes closed, differences in sway velocity also became non-significant [22]. The groups were comparable with respect to age, height, and weight. In addition to this, Matsuda et al. [57], found soccer players to show significantly less sway when standing on the non-dominant leg than on the dominant leg. In this study, the non-dominant leg was defined as the weight-bearing leg in kicking. This difference between legs was only noted in soccer players, not in controls. The only RCT included in this review [56] administered soccer training to the experimental group three times a week for 3 months. Control groups received interval running, moderately intense running, or no training. Soccer training was superior in reducing PS compared with all control groups.

3.3.3 Dancing

Dancers showed less sway with eyes open than controls [7] and soccer players [22] in bipedal stance in one [23] of three studies [23, 32, 34], and less sway in two studies in unipedal stance. With eyes closed, dancers swayed more than controls [23] or practitioners of other sports [32], while no significant differences were detected with controls [32, 34] or practitioners in other sports [22, 33] in the remaining comparisons.

No study found a significantly lower sway for dancers with eyes closed [22, 23, 32–34].

3.3.4 Gymnastics

In bipedal stance, no significant differences were found between gymnasts and experts in other sports [21, 36–38] and gymnasts and controls (practitioners of other sports at a lower level [17]), either with eyes open, or with eyes closed. In unipedal stance with eyes open, one of three studies [17, 37, 38] found a significantly smaller sway area for gymnasts than for controls [17], while the two other studies did not detect significant differences between gymnasts and experts in other sports. In unipedal stance with eyes closed, the opposite was found: no significant differences with controls [17], and a significantly smaller and slower sway than experts in other sports [37].

Table 4 Main findings in comparisons of sport practitioners with control groups[a]

Sport	Bipedal eyes open			Unipedal eyes open			Bipedal eyes closed[b]			Unipedal eyes closed[b]		
	Less	ns	More	Less	ns	More	Less	ns	More	Less	ns	More
Shooting	5 (37)	2 (14)					3 (31)					
Soccer	3 (48)			4 (62)			2 (23)			1 (15)		
Tai Chi	3 (47)			1 (19)			3 (47)					
Judo	1 (17)	1 (11)					1 (17)	1 (11)				
Dancing	1 (18)	2 (31)		1 (53)				1 (17)	2 (32)			
Gymnastics		1 (13)		1 (13)				1 (13)			1 (13)	
Fencers		1 (12)					1 (12)					
Taekwondo		1 (11)					1 (11)					
Triathlon		1 (10)					1 (10)					
Rhythmic Gymnastics		1 (15)						1 (15)				
Surfing		2 (30)										
Golf		1 (17)			1 (17)			1 (17)				
Interval				1 (9)								
Running				1 (12)								
Basketball					2 (19)			2 (19)				
Physical Activity					1 (75)			1 (75)				
Football			1 (9)						1 (9)			
Skiïng			1 (7)						1 (7)			

[a] Main findings in velocity- and amplitude-related variables. Sports compared with control groups with no specific physical activities, or lower level of the same or other sports. Presented are number of studies and (total number of subjects in the sporting groups). Comparisons were considered as less or more sway when one or more of the outcomes significantly differed

[b] Eyes closed, or vision occluded

ns comparisons without significant differences, or with conflicting differences

In bipedal stance with eyes open and eyes closed, female rhythmic gymnasts showed a significantly smaller sway area in the medio-lateral (ML) direction, but a larger area in the anterior–posterior (AP) direction than female non-expert sport students [18]. The rhythmic gymnasts were substantially shorter and lighter than controls.

3.3.5 Tai Chi

Tai Chi practitioners were compared with controls, and showed less sway in all conditions. Three studies [26, 39, 60] were conducted in bipedal stance with eyes open and eyes closed, and one study [26] in bipedal stance with eyes open. The largest differences were found in unipedal stance. The magnitude of the differences between Tai Chi practitioners and controls was comparable in eyes open and eyes closed conditions in all studies.

3.3.6 Judo

Judoists were compared with controls in two studies [32, 55], both using the bipedal stance. With eyes open, judoists swayed less in both studies, although in the study by Paillard et al. [55], the difference was not significant. Perrin et al. [32] found that, with eyes closed, judoists still had a slower and smaller sway than controls, but Paillard et al. [55] found that top judoists showed more and faster sway than judoists at a regional level. The differences in the comparisons by Paillard et al. [55] were not significant, but the interaction between condition and group was. This led the authors to the conclusion that top judoists are more dependent on vision than are controls. The control group used in this study consisted of nine judoists who practiced their sport at a lower level, but with the same amount of training (10–14 h per week).

Perrin et al. [32] also compared top-level male judoists with top-level female dancers. There were no or only small non-significant differences seen with eyes open, but, with eyes closed, judoists swayed significantly less than dancers.

3.3.7 Surfing

Sway variables in surfers, in bipedal stance with eyes open and with eyes closed, were not significantly different from controls [19, 41]. Surfers were studied in bipedal stance

Table 5 Main findings in comparison with sport practitioners of similar level from different sports[a]

	Bipedal eyes open	Unipedal eyes open	Bipedal eyes closed[b]	Unipedal vision occluded[b]
Less sway[c]		Dancing vs. soccer $n = 32$ [22] Soccer vs. basketball and swimming $n = 10$ [27]	Judo vs. dancing $n = 14$ [32]	Gymnastics vs. OS $n = 6$ [37]
Inconclusive	Judo vs. dancing $n = 14$ [32] Gymnastics vs. OS $n = 12$ [21], 7 [38], 6 [37], 7 [36] Dancing vs. track athletes $n = 10$ [33] Shooters vs. fencers $n = 10$ [43]	Gymnastics vs. OS $n = 6$ [37], 7 [38] Basketball vs. swimming $n = 15$ [27] Interval vs. running $n = 9$ [56]	Gymnastics vs. OS $n = 6$ [37], 7 [36] Dancing vs. track athletes $n = 10$ [33] Surfing vs. swimming $n = 21$ [19] Off-road vs. road cycling $n = 20$ [40] Shooters vs. fencers $n = 10$ [43]	Dancing vs. soccer $n = 32$ [22]
More sway	Surfing vs. swimming $n = 21$ [19] Off-road vs. road cycling $n = 20$ [40]			

[a] Main findings in velocity- and amplitude-related variables. The sport mentioned first is the sport of interest in the original study. Comparisons were considered as less or more sway when one or more outcomes significantly differed. Comparisons without significant differences or with conflicting differences were classified as inconclusive. Numbers refer to the number of subjects in the sporting group

[b] Eyes closed, or vision occluded

[c] Less sway indicates smaller CoP velocity or amplitude

OS indicates experts in other sports; [21] experts in handball, track and field, volleyball, table tennis, and football [36] [38]; experts in soccer and handball, [37]; experts in soccer, handball, and tennis

with eyes open and with eyes closed. Compared with swimmers, surfers maintained their balance with eyes open with significantly higher sway velocity [19]. With eyes open, surfers showed more sway as expressed in area- and velocity-related variables than swimmers/waterpolo players and lower-level surfers [19]. The difference in sway velocity with swimmers was significant, but not with eyes closed. Anthropometric differences were of advantage for surfers in comparison with swimmers/waterpolo players.

3.3.8 Running

Nagy et al. [28] compared ten triathletes with ten physically active firemen. After adjustment for relevant confounders, triathletes showed a lower total sway velocity and lower velocities in ML and AP directions, but only with eyes closed. Running as an intervention was used in an RCT to compare the effect of interval running, soccer training, and no training [56]. All three training modalities led to a lesser sway over a period of 12 weeks, but the size of the effect was the largest and most consistent over all sway variables in the group that received soccer training.

3.3.9 Other Sports

Basketball players did not differ significantly from non-sport practitioners [27, 52] and had more sway than soccer players [27]. American football players showed sway levels (velocity and range) comparable to those of obese controls with similar weight, but significantly more than lighter, non-obese controls [53]. Sway velocity of 52 golfers of three different levels, grouped by ‘golf handicap’, was assessed by Stemm et al. [54]. There were no differences in sway velocity between groups, either in bipedal condition, or in unipedal conditions. Road cyclists showed less sway bipedal than off-road cyclists when visual information was available [40]. With closed eyes, the groups no longer differed. Noé and Paillard [42] compared skiers from different levels with each other. Skiers at a national level showed higher velocity and larger area than skiers at the regional level. The differences were significant in area but not in velocity. In an additional condition, wearing ski boots and standing in a skiing position, the effect of expertise reversed: top-level skiers showed less sway on both parameters, although this was not statistically significant. Finally, in Taekwondo practitioners in bipedal stance, a smaller sway amplitude than in non-active controls was found, but this difference was only significant in the eyes closed condition.

3.3.10 General Activity

Ageberg et al. [12] performed two regression analyses, stratified for men and women, with PA in general, weight, and age as independent variables. They corrected for relevant confounders. In a sample of 75 healthy volunteers, they found no association between PA and PS.

4 Discussion

This systematic review identified 39 studies that investigated the relationship between (sport) activities and PS in non-perturbed standing. The main conclusion was that, in general, sport practitioners sway less than controls, and high-level athletes sway less than low-level athletes. Additionally, we identified specific effects dependent on the use of vision, sport-specific postures, and frequency and duration of the (sports) activity.

For every sport or activity, the direction of the significant differences in PS was the same for all conditions. A consistent exception was dancing, in which, with eyes open, dancers tended to show lesser sway than controls and practitioners in other sports, but more sway with eyes closed. A similar interaction was found in a comparison of judoists of different levels.

This is in contrast to the intuitive assumption that the balance-challenging positions and movements that dancers perform should lead to less sway. However, postural control depends on the integration of visual, proprioceptive, and vestibular signals. Dependent on the task, the postural control system can weigh sources of information, making the control system ‘task specific’. In dancing, visual information is a very rich source of information. Visual dominance in sensorimotor integration has previously been proposed to explain findings in dancers [32]. Vision is also a more dominant information source in on-road cycling than in off-road cycling [40]. On-road cyclists indeed showed less sway than off-road cyclists when visual information was available [40], but this better performance diminished when the eyes were closed. Top judoists also seem to depend more on vision than do judoists at a regional level [55], although Perrin et al. [32] found judoists to show less sway than controls who exhibited a low level of PA in both eyes open and eyes closed conditions. We suggest that all balance control systems, visual, proprioceptive, and vestibular, are used in judo, but that the emphasis is on the visual system. For most sports, practitioners depend on proprioceptive and vestibular signals as the primary sources of information. Practitioners of Tai Chi, fencing, taekwondo, and soccer showed, in bipedal stance with eyes open, non-significant differences or less PS than controls. With eyes closed or in unipedal stance, when proprioceptive and vestibular information becomes more important, significant differences stayed significant, and non-significant differences became significant.

The role of vision in gymnastics is less clear. Visual cues can be an important part of gymnastics in some apparatus (i.e., floor and vault), but the emphasis is on proprioceptive and/or vestibular signals in the pommel horse, rings, and bars. Results in gymnasts are all non-significant in bipedal stance, but results in unipedal stance are not consistent. One study only found significant differences with eyes open [17], not with eyes closed, and another study only found significant differences with eyes closed, not with eyes open [37]. In both studies, gymnasts were compared with practitioners of other sports. These findings led to contradictory conclusions about the role of vision in gymnastics. A third study only used the eyes open condition and found no differences. We therefore can only conclude that gymnasts possibly have a reduced PS in unipedal stance.

These findings suggest that balance abilities are specific to a particular task, a hypothesis first posed by Henry [46]. We found more indications that the specific characteristics of a sport or activity cause the varied results in our review. In shooting, bipedal stance with visual focus on the target is the practised position. The positive effect that standing still has on shooting performance is reflected in the direct relationship between the amount of sway and performance, which has been shown in novice shooters [20, 61]. In all included studies, shooters showed less sway, although the difference was not always significant. Specificity of the requirements of the sport was further emphasized by the finding that high-level shooters showed a significant reduction of PS the closer the measurement was to the firing of the shot [20, 25]. Era et al. [20] also observed a more pronounced sway among naive shooters in less successful trials. No studies were performed in conditions other than bipedal stance. To confirm the ‘specificity hypothesis’ for shooters, studies in which shooters are compared with sport practitioners in non-sport-specific conditions (e.g. unipedal) will be of value.

Besides the systematically reviewed conditions, several other tests that have been performed in the included studies strengthen the idea of a condition- and task-specific relationship between activities in sport and PS. Differences between shooters and controls increased when an aiming position was taken [29], and for soccer players on seesaws, smaller effect sizes were found for national-level than for regional-level soccer players [30]. This led Paillard et al. [30], to the conclusion that better performance is only seen in soccer-specific test conditions. In another study, national-level skiers showed more sway than regional-level skiers. In a position that reflected the specific sports activity, wearing skiboots and standing in a 100° knee angle, the differences between groups vanished [42]. Furthermore, better postural control in (inter)national level surfers than in regional level surfers, only became manifest on an unstable surface [41]. In soccer players, specificity of the sports activity was even seen in a comparison between the legs. Differences between national- and regional-level soccer players were significantly larger when standing on the non-dominant leg [57]. Running, and activity in general, can be considered as an activity that requires only small balance capacities. Ageberg et al. [12] did not find an effect of PA in general, but Nagy et al. [28] found that triathletes showed lower sway velocity with eyes closed than physically active fire-fighters. The most striking difference between these two studies is the extremely high level of PA in the group of triathletes. These findings are in line with the study by Jakobsen et al. [56], which was the only included study with an RCT design. In this study, a training program consisting of 12 weeks continuous endurance running led to small and not always significant minimizing effects on sway velocity and area, while a training program consisting of high-intensity interval training led to larger and significant effects on PS. However, both programs had significantly less effect on sway than a soccer training program. An explanation for the findings in these studies could be the influence of duration and intensity on the effect on PS. Although running does not require many balance-challenging tasks, when practised for long and intensively enough, there still seems to be an effect on PS. In our review, ten studies noted significant differences in PA level, and ten studies did not report the PA level of participants. This poses a potential threat to the validity of our conclusions. In our opinion, the chances of confounding in this review are not large, because PA levels are most likely not as extreme as in triathletes, most of these studies examined sports that were also included in studies with no significant differences in PA between groups, and in some cases even more sway was measured for the group with the highest PA level [23]. However, future studies into the specific effects of a sport or activity should take equality of PA between the groups into account.

Next to practising a sport, the differences in PS could also have a genetic or developmental cause. Perhaps the capacity to control PS in a specific condition is a prerequisite to becoming a high-level athlete. This review cannot sufficiently distinguish between cause and consequence. Only one prospective RCT was included, which did support an effect of sports activity on PS. On the other hand, Paillard et al. [55] used a design in which the higher level of sports practice in one of the studied groups was likely due to being more talented and not the result of practice. In this study, judoists in both groups trained for the same amount of time, but only differed in level of competence. With a sample size of 11 judoists, they found an almost significant advantage for the higher level judoists with eyes open, which disappeared when eyes were closed.

Of all studies, 37 % detected significant differences in bipedal stance with eyes open, 68 % in unipedal eyes open, 55 % in bipedal eyes closed, and 50 % of just four studies in unipedal stance with eyes closed. Furthermore, in all sports that were investigated in bipedal stance with eyes open, differences between sport practitioners and controls were replicated in more challenging conditions (unipedal or eyes closed; soccer, judo, golf, football, skiing), or more pronounced (shooting, Tai Chi, gymnastics, fencing, taekwondo, triathlon). This suggests that bipedal standing quietly on a solid surface, bipedal, with eyes open is not a challenging enough task to detect small differences in PS between groups of sport practitioners. There is another indication that supports this hypothesis. In some of the included studies, manipulations of the standing surface, surroundings, or distraction of the participant were performed as an extra task. Almost every extra task resulted in larger differences between sport practitioners and controls. Only one study did find results in standing but not in a more challenging condition, imposed by using a seesaw device [30].

In light of this evidence, more challenging tasks, like standing on foam or standing in unipedal stance, should be considered in addition to the standard bipedal task.

Additional to a more challenging task, it seems plausible that the kind of verbal instruction also at least partly determines the amount of sway. Seven of the 39 studies in this review did not report which instruction was given. To make future studies more comparable, it is advisable that participants are told to stand as still as possible or at least that the specific instruction is reported. With respect to sensitivity, no conclusion can be drawn about the differences between area- and velocity-related variables.

Six included studies [17, 19, 28, 30–32, 34] stated explicitly that lower velocity or area in PS in normal stance corresponds with better postural control. It is questionable whether this assumption is true by definition.

Human sensory systems are better equipped to register changes in information than to cope with unchanging conditions and therefore richness of information might increase the stability and adaptability of the postural system [62]. In a completely static posture, without any movements of the body, there is less information available to guide the motor system in accomplishing the complex balance task of standing upright. Hence, sway might be seen as an adequate solution in quasi-static conditions and maybe the variation in the structure of PS provides a better indicator for 'dynamic balance' capacities. Among the studies included in this review, only Schmit et al. [33] analyzed the structure of the PS by means of RQA. They compared student dancers with track athletes and in contrast with standard measures of PS in bipedal stance, non-linear variables strongly differentiated dancers from controls. Dancers showed less regular patterns of sway. Previous research in a population with patients with Parkinson's disease [63] and stroke [64], and research among sport practitioners by means of accelometry [65], suggests that less regular patterns of sway are a characteristic of increased postural stability. Analyzing the regularity of the CoP pattern does not require extra effort in the experimental setup. Therefore, it seems worthwhile to also perform non-linear analyses in future studies.

This review exposed some limits of comparative studies on PS. One of these is the duration of the trial. Reliability of postural stability measures increases with an increase in length of the trial, or by averaging more than one trial [66, 67]. Carpenter et al. [67] advised a measurement duration from 60 to 120 s. Of the 39 included studies, 18 used a measurement time of 30 s, which could have led to type II errors.

Most studies did not report raw data per tested condition (i.e. means and standard deviations) or effect sizes. Therefore a meta-analysis could not be performed, while the similarity of experimental set ups and populations would have made a meta-analysis meaningful.

5 Conclusion

This review demonstrates that, in general, sport practitioners sway less than controls in unperturbed stance. An additional effect of activity on PS is specific for the activity or sport that is being performed. The use of vision, sport-specific postures, and frequency and duration are important characteristics that determine the effect of sports activity on PS in standing.

Sway area and velocity in unperturbed bipedal stance appear to have limited sensitivity to detect subtle differences between groups of healthy people. Other conditions, like standing on foam or unipedal stance, should be used when healthy people are studied.

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