Effects of personal and task constraints on limb coordination during walking: a systematic review and meta-analysis

SHAFIZADEH, Mohsen <http://orcid.org/0000-0002-7524-1058>, CROWTHER, Robert, WHEAT, Jonathan <http://orcid.org/0000-0002-1107-6452> and DAVIDS, Keith <http://orcid.org/0000-0003-1398-6123>

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Effects of personal and task constraints on limb coordination during walking: A systematic review and meta-analysis

Mohsen Shafizadeh[1], Robert Crowther[2], Jonathan Wheat[1], Keith Davids[3]

1-Faculty of Health and Wellbeing, Sheffield Hallam University, UK

2-School of Health Sciences, University of South Australia, Australia

3-Centre for Sport Engineering Research, Sheffield Hallam University, UK

Corresponding author: Mohsen Shafizadeh, Faculty of Health and Wellbeing, Sheffield Hallam University, Sheffield, S10 2BP, UK.

Email: m.shafizadeh@shu.ac.uk

Abstract

Background: In human behaviour, emergence of movement patterns is shaped by different, interacting constraints and consequently, individuals with motor disorders usually display distinctive lower limb coordination modes.

Objectives: To review existing evidence on the effects of motor disorders and different task constraints on emergent coordination patterns during walking, and to examine the clinical significance of task constraints on gait coordination in people with motor disorders.

Methods: The search included CINHAL Plus, MEDLINE, HSNAE, SPORTDiscus, Scopus, Pubmed and AMED. We included studies that compared intra-limb and inter-limb coordination during gait between individuals with a motor disorder and able-bodied individuals, and under different task constraints. Two reviewers independently examined the quality of studies by using the Newcastle Ottawa Scale-cohort study.

Findings: From the search results, we identified1416 articles that studied gait patterns and further analysis resulted in 33 articles for systematic review and 18 articles for meta-analysis-1, and 10 articles for meta-analysis-2. In total, the gait patterns of 539 patients and 358 able-bodied participants were analysed in the sampled studies. Results of the meta-analysis for group comparisons revealed a low effect size for group differences (ES= -0.24), and a moderate effect size for task interventions (ES= -0.53), on limb coordination during gait.

Interpretation: Findings demonstrated that motor disorders can be considered as an individual constraint, significantly altering gait patterns. These findings suggest that gait should be interpreted as functional adaptation to changing personal constraints, rather than as an abnormality. Results imply that designing gait interventions, through modifying locomotion tasks, can facilitate the emergent re-organisation of inter-limb coordination patterns during rehabilitation.

Keywords: Emergence, constraints, functional adaptations, motor disorder, gait, coordination patterns, meta-analysis.

1. Introduction

The re-organisation of joint degrees of freedom (DoFs) in a neuromusculoskeletal (NMS) system supports functionality in performance of everyday movement tasks. The central nervous system (CNS) solves the DoFs problem through creating functional units, coordinative structures or motor synergies, at the level of both muscles (e.g. motor unit) and limbs (e.g. joint), in order to organise a movement pattern and accommodate environmental demands (Bernstein, 1967). The multi-segment synergies that emerge in the NMS system increase performance adaptability for two main purposes: maintaining system stability and dealing with possible internal and external perturbations (Latash, Scholz, & Schoner, 2007; Latash, 2012). It has been revealed that kinematic coupling or synergy formation, underlying a movement pattern, is an informational resource during performance of rhythmic actions such as bimanual coordination and gait (Wilson, Collins, & Bingham, 2005). Coordination between two segments, as a simple version of a motor synergy, is an important feature of movement behaviour in synchronising spatiotemporal activity of involved muscle groups into coherent, functional patterns (Kelso, 1984). The main function of a coordinative pattern, like other synergic segments, is to ensure that the adjacent joints, as in intra-limb coordination, or contralateral segments, as in inter-limb coordination, work together so that limb stability is maintained under all conditions. For example, thigh and shank segments, as a coupled unit, play a significant role in maintaining postural stability before heel-contact in gait (Fowler & Goldberg, 2009). Any malfunction or perturbation, due to timing or range of motion, in this coupled unit could affect gait performance and influence risk of falling (Sutherland & Davids, 1993).

Inter-limb and intra-limb coordination patterns that (re)emerge from the coupling between different segments during walking are shaped by individual, environment and task constraints. According to Dynamic Systems Theory (DST), the self-organisation of motor behaviour is regulated by the dynamic interactions between these different constraints (Newell, 1986; Diedrich & Warren, 1995). Constraints in turn influence the emergence of an adaptive control system to facilitate functional movement compensation due to injury, motor disorders, under specific environmental conditions (e.g. walking on unstable or slippery surfaces, or on uphill/downhill slopes). For example, walking in different environmental conditions (on clear versus cluttered surfaces) requires continuous spatial perception and adaptations in foot trajectories to maintain balance. This interaction between task and environmental constraints could also be affected by relevant personal constraints, such as injuries or motor disorders. Motor disorders are malfunctions of the nervous system that cause involuntary or uncontrollable movements or actions of the body (Stone, 2015).

A common way to quantify inter-limb coordination or intra-limb coordination is through measuring the amount of coupling between adjacent segments, using relative phase (RP) values that range from 0-180 degrees. Zero and 180 degrees are classified as stable coordination patterns, whereas any relative phase values between them have not been considered to be as stable (Haken, Kelso & Bunz, 1985). The interpretation of such measurement scales in functional movements, such as gait, is rather limited because there is no absolute cut-off point to interpret the results based on average RP values (Van Emmerik, Hamill, & McDermott, 2005).

It has been suggested that coordination variability (cycle-to-cycle changes) is a better representation of the dynamic nature of human movement, and its association with other factors, such as ageing and motor disorder (Hamill, Van Emmerik, Heiderscheit, & Li, 1999). For instance, a lack of variability in coordination dynamics during gait has been associated with an inability to transit from one pattern to another in individuals with Parkinson's disease (Van Emmerik, Wagenaar, Winogrodzka, & Wolters, 1999). Reduced joint variability, as coordination variability, and larger spatiotemporal variability, as outcome variability, have been observed in individuals with motor disabilities (Heiderscheit, 2000). The former is an index of adaptability, whereas the latter represents a risk of falling if it exceeds critical threshold values. Evidence suggests that the adaptability of motor system is changed by neurological and skeletal disorders, and that functional variability in movement patterns need to be re-emphasised in gait (re)training interventions (Jeng, Holt, Fetter, & Certo, 1996; Hamill, et al., 1999; Heiderscheit, Hamill, & van Emmerik, 2002; Papi, Rowe, & Pomeroy, 2015; Black, Smith, Wu, & Ulrich, 2007).

For this reason, pathological gait has been studied to reveal the underlying mechanisms that change walking movements, and research has been focused on measures such as spatiotemporal parameters (Del Olmo & Cudeiro, 2005; Crenshaw & Royer, 2006; Heiderscheit, et al., 2002), gait symmetry (Yogev, Plotnik, Peretz, Giladi, & Hausdorff, 2007), muscle activity (Miller, Thaut, McInotsh, & Rice, 1996) and limb coordination (Giannini & Perell, 2005; Stolze et al., 2002). Quantification of gait under dynamic performance conditions, and in individuals with a motor disorder, is a method to understand how pathological conditions may constrain movement pattern re-organisation, due to muscle weaknesses and spasticity in involved muscle groups (Nutt, Marsden, & Thompson, 1993; Shumway-cook & Wollacott, 2007). However, types of gait assessment vary in clinical settings, but by using objective measures such as spatiotemporal outcomes and relative phase, quantification of gait disorders can be more rigorous, comparable and consistent in the assessment process. From this point of view, it is plausible to study gait for two main purposes: first, to compare between normal and compensatory gait patterns and second, to assess the effectiveness of specific interventions on the gait adaptations. These two perspectives are used in this study according to a constraints-led approach (Davids, Button & Bennett, 2008). A comparison between able-bodied and patient groups emphasises the role of a condition, disorder as a type of organismic (personal) constraint. On the other hand, different gait re-training interventions can serve as task constraints to facilitate functional gait adaptations required as compensations for the existence of personal constraints.

Some previous review studies have examined variability of spatiotemporal characteristics in gait of older individuals with fear of falling (Ayoubi, Cyrille, Launay, Annweiler and Beauchet, 2015) and in individuals with neurological conditions (Moon, Sung, An, Hernandez, & Sosnoff, 2016). Barton, Levinger, Menz and Webster (2009) studied angular kinematics such as joint motions in different planes in individuals with patellofemoral pain syndrome. Other systematic reviews have studied the efficacy of gait re-training for improving overall performance of gait in individuals with neurological problems (Manning & Pomeroy, 2003) and also coordination in post-stroke patients (Hollands, Pelton, Tyson, Hollands, & van Vliet, 2011). Previous systematic reviews that have investigated abnormal gait were different in scope from the current study in terms of populations investigated and their gait characteristics. First, none of the above-mentioned studies have reviewed gait coordination in individuals with a motor disorder and the effects of task constraints on observed coordination patterns. Second, the current study, unlike that of Hollands et al. (2011), is not limited to stroke patients and includes all studies of individuals with motor disorders due to long-term neurological conditions and musculoskeletal problems. This, in turn, could explain the effect of diverse types of disorder as personal constraints on gait patterns. Third, the research design of the current study included an able-bodied control group, instead of a placebo group. Finally, previous quantitative reviews have not separately analysed relative phase and limb couplings (e.g. cross-correlation) as measures of movement coordination, compared to velocity, acceleration and symmetry indices (Krasovsky & Levin, 2010).

An emphasis on improving gait outcomes in rehabilitation programmes, framed by a theoretical understanding of movement coordination, evidenced by changes in joint kinematics and kinetics due to muscle weaknesses and spasticity (Thompson & Nutt, 2012), is informative for allied health practitioners who seek to understand how to improve mobility through gait re-training. Thus, the aims of this systematic review and meta-analysis were to review the existing studies that examined the effects of motor disorders and task constraints on coordination patterns during locomotion and to understand whether interventions manipulating task constraints have any clinical significant effects on gait coordination in individuals with motor disorders.

2. Methods

2.1. Eligibility criteria

Studies that met the following criteria were included in the systematic review. 1- The research designs sampled included cross-sectional, cohort based, pre-post designs or studies with randomised control trials (RCT). 2- The population included patients and able-bodied individuals. 3- The gait setting was either walking on a treadmill or over-ground. 4- Gait interventions included treadmill walking, walking under dual-task constraints, robot walking, walking at different paces or walking while obstacle crossing. 5- The article type was peer-reviewed publications in English.

Studies that were excluded when: 1-There was no control group/condition for comparison for a meta-analysis. 2- They were case-study and non-peer reviewed articles. 3- They lacked any coordination measurements.

2.2. Search strategy

The search was carried out in Cumulative Index to Nursing and Allied Health Literature (CINHAL), MEDLINE, Health Source: Nursing/ Academic Edition (HSNAE), SPORTDiscus, Scopus, Pubmed, Cochran Library and Allied and Complementary Medicine

Database (AMED). The search strategy involved 3 distinct steps and each time a combination of 3 to 4 terms were used. The selected terms were chosen because they were representative of the variables of study and the measurement methods in quantification of gait pattern. In the first step, a combination of keywords from the "coordination" AND "walking" AND "patients" was used together. Then, the combination of "coordination" AND "variability" AND "patients" AND "walking" was used together. Finally, the combination of "relative phase" AND "patients" AND "gait" was used together. Each time the combined terms search brought new studies, of which some were already included in our study and some were removed from the final list of studies.

2.3. Study selection

The studies that were identified through search were selected for in depth screening according to the selection criteria. Studies that were selected for group comparisons (aim 1) and task constraints (aim 2) were grouped separately for further analysis. All abstracts and full texts were screened by MS.

2.4. Data collection process

The data extraction procedure was performed by creating a spreadsheet to sort studies according to the main inclusion criteria. Studies were organised in a Microsoft Excel worksheet according to methodological and research outcome information. The methodological elements were sample size, participants groups, walking setting and gait training mode. Gait measures analysed were different types of coordination patterns (please see section 2.7 for more information about coordination index).

2.5. Synthesis of results

A meta-analysis was performed to calculate the pooled effect size (ES) for coordination pattern indices between groups of patients and able-bodied individuals and between baseline and intervention conditions. A random-effect model was used at a confidence interval 95% using Cochran's Q test and I^2 statistics as indices of heterogeneity (above 40%). A random effects model also accounts for differences in variability across studies by weighting each standardized effect on the basis of its standard error. The Q statistic is the sum of squares of the weighted mean standardized effect of each study within each variable (coordination index) divided by the overall weighted mean standardized effect for that variable. Standardized effects indicate the magnitude of an independent variable, regardless of sample size. The independent groups in this study were able-bodied/patients and dependent groups were baseline/intervention. Standardized effects were calculated for each variable as the difference between groups means (e.g. able-bodied-patients; baseline-intervention) divided by the group pooled standard deviation. A standardized effect size of less than 0.2 was considered trivial, 0.2-0.5 was considered small, of 0.5-0.8 was considered moderate and above 0.8 was considered large (Cohen, 1988). If in a study there was more than one outcome for coordination pattern, then a synthetic score was used - the average (mean) of separate ES's for each dependent variable.

There are several ways to interpret the clinical significance of changes or differences reported in the studies (Page, 2014). Clinical relevance changes in the outcome usually are assessed by methods that quantify the minimal clinically important differences (MCID) such as using standard deviation (SD), standard error of mean (SEM), anchored-based methods (Rai, Yazdany, Fortin, & Avina-Zubieta, 2015), confidence intervals and magnitude-based inferences (Hopkins, Marshal, Batterham, & Hanin, 2009). The method that was used in this study to assess MCID was using 0.2 (SD). First, the pooled SD of groups and a mean difference between groups (e.g. patients/able-bodied; baseline/intervention) were calculated.

If the value of mean difference was greater than the pooled SD, the ES was deemed to be clinically significant (Lemieux, Beaton, Hogg-Johnson, Bordeleau, & Goodwin, 2007). All statistical analyses were conducted in Review Manager 5.3.3 version (Nordic Cochrane Centre). The statistical significance level was set at $p<0.05$; two-tailed.

2.6. Study quality assessment

The quality of study was assessed by Newcastle-Ottawa Quality Assessment Scale-cohort study (Wells, et al., 2005). This assessment scale has two versions: one for a case study and one for a cohort study. The cohort version was used in the current study. The scale has 8 items and 3 subscales including selection (4 items), comparability (1 item) and outcome (3 items). The "selection subscale" assesses the quality of a study in terms of the representativeness of the selected participants, whether the group was non-exposed, the source of access to the sample and blindness. The "comparability subscale" mainly assesses the control of confounding factors. The "outcome subscale" assesses the method of data collection such as design, number of data collection sessions, and the survival rate in follow-up tests. The possible total score in each study ranges between 0 and 9. MS and RC conducted the quality assessment independently by using all above-mentioned items and if there was a disagreement on scores it was resolved through discussion.

2.7. Additional analyses

Intra- and inter-limb kinematic coordination patterns were interpreted differently in this study. For inter-limb coordination patterns, the mean scores and SD of means, phase coordination index (Plotnik, Giladi, & Hausdorff, 2009), absolute relative phase (Roerdink, Lamoth, Kwakkel, van Wieringen, & Beek, 2007) and asymmetry index (St-Onge, Duval, Yahia, & Feldman, 2004) were used for further analysis. The higher values, in all indices, represent less symmetry between contralateral limbs or segments. For intra-limb coordination patterns, established variability indices, such as SD or CV, deviation phase (Chiu, Lu, & Chou, 2010), decomposition index (Mian, Schneider, Schwingenschuh, Bhatia, & Day, 2011) and average coefficient of correspondence (Daley, Sng, Roenigk, Fredrickson, & Dohring, 2007), were used to represent the quality of coordination in terms of consistency (repeatability) and variability. The higher values in variability indices and average coefficient of correspondence represent greater flexibility and consistency among coupled segments, whereas higher values in deviation phase and decomposition index represent less consistency and coupling among adjacent segments.

3. Results

3.1. Search results

The search results yielded 1416 articles that reported studies of gait in patients. More specifically, the searches with a combination of terms like "coordination" AND "walking" AND "patients" brought up 992 articles. Searching with a combination of "coordination" AND "variability" AND "patients" AND "walking" and with a combination of "relative phase" AND "patients" AND "gait" resulted in 122 and 302 articles, respectively (see Figure1). Some articles were excluded due to duplication in the searches (n=296). The majority of studies that examined gait in the patient groups were focused on the kinematics (e.g. range of motion) or kinetics (ground reaction force) and muscle activity (e.g. EMG). Since these types of measurements were not appropriate to quantify the kinematic coordination patterns, they were excluded in this study (n=1087). After further inspections of the abstracts (excluded studies=957) and the main body of text (excluded studies=130), they were excluded because they could not provide further information about assessment of kinematic coordination patterns during gait. In the next stage, 33 articles, which were related to kinematics coordination and only gait patterning, were selected for systematic review (see Table 1 for the list of studies). The final numbers of studies, without duplications were: (i) 15 articles with a combination of "coordination" AND "walking" AND "patients"; (ii) 8 new articles with a combination of "coordination" AND "variability" AND "patients" AND "walking"; and (iii),10 new articles with a combination of "relative phase" AND "patients" AND "gait". From this selection, 18 articles were selected for meta-analysis-1 (see Figure 1) on coordination differences between able-bodied individuals and patients (Chiu, et al., 2010; Combs, Dugan, Ozimek, & Curtis, 2013; Daly, et al., 2007; Gianni & Perell, 2005; Heiderscheit et al., 2002; Hoogkamer et al., 2015; Hutin et al., 2011; Hutin et al., 2012; Meyns et al., 2012; Meyns, Molenaers, Desloovere, & Duysens, 2014; Mian, et al., 2011; Nanhoe-Mahabier et al., 2013; Peterson, Plotnik, Hausdorff, & Earhart, 2012; Plotnik, et al., 2009; Roerdink, et al., 2007; St-Onge, et al., 2004; Shafizadeh, Watson, & Mohammadi, 2013; Wang et al., 2009) and 10 articles were selected for meta-analysis-2 on the effects of task constraints on gait coordination pattern (Combs, et al., 2013; Daly, et al., 2007; Hutin et al., 2012; Lewek et al., 2009; Nanhoe-Mahabier et al., 2013; Peterson, et al., 2012; Plotnik, et al., 2009; Plotnik, Giladi, Dagan, & Hausdorff, 2011b; Roerdink, et al., 2007; Wang, et al., 2009).

3.2. Quality assessment

MS and RC read the full texts and independently assessed the quality of selected studies for qualitative review. The result of quality assessment score for each study is presented in Table 1. The mean quality score for 33 studies that were included was 6 out of 9 and ranged between 4 (Hoogkamer et al., 2015) and 8 (Chiu et al., 2010). The common methodological issues in these studies based on quality scale were selection of a non-exposed cohort (item 2) and adequacy of follow-up of cohorts (item 8). Some studies also had only one group in their research design (Alice, et al., 2007; Fowler, et al., 2009; Lewek, et al., 2009; Plotnik, et al., 2011b) or had a small sample size (Barela, et al., 2000; St-Onge, et al., 2004). Studies that were investigated in meta-analysis 2 tended to have a higher quality score among the selected articles in this systematic review.

Insert Table 1 here

3.3. Qualitative synthesis

In total 539 patients and 358 able-bodied participants were selected for testing the coordination pattern in gait analysis. The types of diseases in the patient groups were Stroke: 9 studies; Cerebral Palsy; 3 studies, Cerebellar Ataxia: 3 studies, Parkinson disease: 9 studies, Multiple Sclerosis: 1 study, Huntington's Disease: 1 study, Spinal Cord Injury: 1 study, Osteoarthritis: 3 studies and hip and knee pain: 3 studies. The smallest sample size was 5 (Daly et al., 2007) and highest was 34 (Plotnik et al., 2008).

The most common methods for quantification of limb coordination were inter-limb (13 studies) and intra-limb (22 studies) as forms of hip-knee (17 studies) and knee-ankle coupling (12 studies).

Two studies (Barela et al., 2000; Lewek et al., 2009) reported average coefficients of correspondence (ACC) to quantify the coordination between two segments. Seven studies (Plotnik et al., 2009, Plotnik et al., 2011a, 2011b and Plotnik et al., 2008; Peterson et al., 2012; Nanhoie-Mahbier et al., 2013; St-Onge et al., 2004) used Phase Coordination Index (PCI) method. Twenty studies (Daly et al., 2007; Shafizadeh et al., 2013; Heiderscheit et al., 2002; Hutin et al., 2012; Hutin et al., 2011; Combs et al., 2013; Fowler et al., 2009; Hoogkamer et al., 2015; Wang et al., 2009; Liu et al., 2014; Chiu et al., 2010; Meyns et al., 2014; Meyns et al., 2012; Rinaldi et al., 2013; Mian et al., 2011; Ornetti et al., 2011; Awai &Curt., 2014; Serrao et al., 2012; Tanahashi et al., 2013; Roerdink et al., 2007) reported continuous relative phase (CRP) as an index of coordination. Four studies (Reynolds, et al., 1999; Stolze et al., 2002; Alice et al., 2007; Gianni and Perell, 2005) used angle-angle plot to illustrate the coordination between joints. A treadmill was used as a walking context for 6 studies and in 17 studies a walkway was used. The methods of gait re-training included walking at different speeds (4 studies), treadmill training (2 studies), gait tasks in different conditions (4 studies), dual-tasking during walking (3 studies) and robot training (1 study).

Insert Figure 1 here

Insert Table 2 here

3.4. Meta-analysis

3.4.1. Effect of motor disorders

The results of the meta-analysis for comparison between synergetic characteristics of gait in able-bodied and patients groups showed an overall statistically significant difference between samples (ES_{mean}= -0.24, Z=2.34, $p<0.05$). The ranges of effect size among individual studies were between 0.08 and -3.95 (see Figure 2). Cochran Q^2 results showed low heterogeneity (Q^2=1.32, I^2=1%) among studies that was less than 40% and acceptable. The participants in the able-bodied group displayed both a greater consistency in creating a synergic unit between adjacent segments and also had greater symmetric coordination between contralateral limbs.

In intra-limb coordination, Daly et al. (2007) highlighted less consistency in a patient group, relative to an able-bodied group. Shafizadeh et al. (2013) also showed a more instable phase lag (close to 90˚) between segments in a patient group. While Gianni and Perell (2005) showed more coordination variability in an able-bodied group, Hutin, et al. (2012) showed more variability in a patient group. The studies that examined inter-limb coordination (Combs, et al., 2013; Hoogkamer, et al., 2015; Peterson, et al., 2012; Plotnik, et al., 2009; Roerdink, et al., 2007) collectively showed that the patients displayed asymmetrical inter-limb coordination. The mean asymmetry index value in the able-bodied group, in all studies, was lower than in the patient groups.

The results of MCID showed that the findings reported in the majority of studies were clinically significant outlining an abnormal coordination pattern in patient groups. As shown in Table 2, the mean group difference was greater than the pooled SD in the most of the studies, and only in 2 studies (Hutin et al, 2011; Meyns et al, 2014) the clinically abnormal coordination pattern was not displayed.

Insert Figure 2 here

Insert Table 3 here

3.4.2. Effect of task constraints

The results of a meta-analysis for comparison between baseline and interventions in patients showed a significant main effect of task constraints on gait coordination (ES_{mean}= -0.53, Z=4.58, $p<0.05$). The ranges of ESs were between 0.08 and -3.13 in favour of intervention (see Figure 3). Cochran Q^2 results revealed low heterogeneity (Q^2=0.33, I^2=0.8%) among studies that was less than 40% and acceptable.

Inspection of studies revealed a statistically significant ES which suggests the effect of task constraints was statistically significant only on inter-limb coordination patterns (Nanhoie-Mahbier et al., 2013; Peterson, et al., 2012; Plotnik, et al., 2009; Plotnik, et al., 2011). In other words, the interventions, such as using a split-belt treadmill, forward/ backward walking and dual-tasking, resulted in a greater inter-limb asymmetry relative to the baseline condition. The results of MCID (see Table 3) also confirmed that the same studies, along with Roerdink et al. (2007), revealed clinically significant effects, and they showed how these walking task constraints perturbed the coordination patterns.

Insert Figure 3 here

4. Discussion

The aims of this study were to review the existing studies that have examined the effects of motor disorders and task constraints on coordination patterns and to understand whether interventions involving task constraints have any clinically significant effects on gait coordination in individuals with motor disorders. Studies that have used inter-limb and intra-limb coordination patterns were selected for systematic review, and if they have reported coordination index values, were selected for meta-analysis. Since the majority of studies found in initial searching (n=1087) did not meet the selection criteria of including data on coordination patterns, walking patterns and kinematics, they were excluded from this study. In total, 33 studies met the selection criteria for systematic review, 18 studies were selected for meta-analysis with the aim of comparison between able-bodied individuals and patients, and 10 studies were selected for meta-analysis with the aim of pre-post intervention comparisons. The remaining studies (n=5) did not meet the criteria for meta-analysis, through a lack of a control group or an intervention, and were only used for the systematic review. The majority of studies (n=20) used relative phase as a coordination index. The studies that were selected mainly used one group for gait assessment and had no follow-up assessments, which are important elements of experimental studies. The studies that were used for meta-analysis 2 displayed a higher quality in terms of research design.

4.1. Coordination patterns deteriorate with motor disorder

One of the main findings of this study was the effect of motor disorder on coordination patterns during walking. The results of a meta-analysis revealed an overall effect of group difference that was statistically significant with an average ES of -0.24. This effect is small according to Cohen’s classification (Cohen, 1988). Furthermore, the results of MCID showed that the findings of studies that had small to very large ESs (>0.1) were clinically significant.

In fact, the motor disorder has a harmful role on the emergent gait coordination patterns. Only findings in 2 studies (Hutin et al, 2011; Meyns et al., 2014) that had a very trivial ES (0.08) were not clinically significant. These results are important as they were not dependent on any statistically significant ES value.

The interpretation of group differences depends on the nature of coordination patterns. For example, for studies that examined inter-limb coordination patterns, the common way to quantify the gait pattern was through PCI and absolute relative phase that measure the coordination pattern relative to a symmetric pattern. From this point of view, the highest difference represents less symmetric inter-limb coordination. The studies that examined inter-limb patterns supported this finding that inter-limb coordination in individuals with motor disorders was different from able-bodied people and has asymmetric phase coupling (Plotnic et al., 2009; Roerdink et al., 2007, Peterson et al., 2012).

The effects of disorder on limb movements, especially in functional movements that require rhythm and repetitive cyclic motion such as gait due to spasticity, insufficient passive range of motion and weak voluntary muscle contractions, are destructive (Hutin et al., 2012). Some suggested mechanisms that specifically constrained inter-limb coordination variability in end-effectors (Roerdink et al., 2007). In a study of individuals with stroke, Roerdink et al. (2007) reported an asymmetric coordination between paretic and non-paretic legs in heel-strike variability. In fact, variability was greater in the paretic leg. The same results were reported in individuals with Parkinson’s disease who displayed a freezing of gait. For example, Peterson et al. (2012) showed that deviation from a symmetric inter-limb coordination was greater during walking tasks that included more cognitive and motor challenges, such as backward walking and turning whilst walking. These findings supported the idea that the interaction of task and individual constraints due to changes in body systems hindered walking performance.

The results of the current study showed that the able-bodied group displayed greater consistency in creating a synergic unit between adjacent segments. More specifically, intra-limb coordination was less consistent (Daly, et al., 2007), displaying more unstable phase lags between segments (Shafizadeh et al., 2013; Gianni & Perell, 2005) in the patient group. While inter-limb coordination represents the amount of symmetry in contralateral limbs, intralimb coordination is representative of kinematic synergies between adjacent segments. The coupled unit underlying a gait pattern acts as an informational resource (Wilson et al., 2005) and provides information about the stability and consistency of the synergic units. The use of multi-segment synergies increases the adaptability of a movement system to maintain system stability in dealing with possible internal and external perturbations (Latash, et al., 2007; Latash, 2012). Synergy between adjacent limbs facilitates body transport and postural stability in an effective and energy efficient manner (Water et al., 1988). Changing this functional synergy as a form of compensation, following musculoskeletal or neurological diseases, could increase the risk of falling (Dean & Kautz, 2015). In addition, a lack of variability in coordination dynamics during gait was associated with a poor phase transition between different walking patterns in people with Parkinson's disease (Van Emmerik, et al., 1999).

The multi-segment synergy among adjacent joints plays an important role in different phases of gait. The shank-foot coordination pattern in late stance and pre-swing is important for energy transfer (Giannini & Perell, 2005), and thigh-shank coordination is required for forward progression of the opposite leg in the stance phase (Daly, et al., 2007; Waters, Barnes, Husserl, Silver, & Liss, 1988) and for maintaining postural stability before the heel-contact (Fowler & Goldberg, 2009).

Losing these functional synergic units could affect gait performance. For example, Combs et al. (2013) demonstrated that paretic leg in stroke survivors, during the swing phase, had a slight lag in timing, revealed by CRP analysis to be in anti-phase. Similar results were reported by Barela et al. (2000), Giannini and Perell (2005) and Chin, Rosie, Irving, and Smith (1982) in the paretic leg in the pre-swing phase. Recently, Chow and Stokic (2015) showed that a delayed peak and inability to sustain peak hip flexion during the transition from swing to stance phases was associated with altered intersegmental coordination in the paretic limb after stroke. Uncoordinated movement among adjacent segments, during walking, might lead to postural instability and poor adaptations to internal and external perturbations (Latash, et al., 2007; Sutherland & Davids, 1993).

4.2. Task modifications constrain the gait coordination pattern

Another main finding of the current study was the significant main effect of task constraints on coordination pattern. The meta-analysis on comparisons between baseline and intervention conditions resulted in an ES value of -0.53, classified as a medium effect (Cohen, 1988). The results of MCID also showed that the clinical effectiveness of such interventions, to some extent, was associated with the magnitude of the ES; ES values greater than (0.50) led to a clinically significant change. The only study that reported a clinically significant change with a small ES value (-0.26) was that of Roerdink et al. (2007), which could be related to its small sample size.

The modes of gait re-training in the selected studies were different and mainly consisted of treadmill training (Nahoe-mahbier, et al., 2013; Roerdink, et al., 2007; Combs, et al., 2013), walking at varied speeds (Hutin, et al., 2012), dual-tasking (Plotnik, et al., 2009; Plotnik et al., 2011b), performance of different walking activities (Peterson, et al., 2012; Wang, et al., 2009; Daly, et al., 2007) and walking with robotic aids (Lewek, et al., 2009). Inspection of the studies that reported clinical significant changes following the walking tasks showed that they used smaller training volume (repetition/ frequency/length) than other studies (see Table

4). This finding might explain how changes in coordination patterns observed following these types of interventions, may have temporarily destabilised gait patterns, instead of inducing long-term adaptations. In fact, forcing patients to walk in unusual or novel (Peterson, et al., 2012) conditions makes coordination patterns less stable because a high level of physical or cognitive constraint on limb movement is induced as individuals need to adapt to new challenges. However, it is not straightforward to determine an optimal period for coordination adaptation in new and challenging walking tasks due to intra and inter-individual variability. It seems that one of the key task constraints that should be emphasised is walking practice in challenging situations in order to facilitate the stabilisation and re-stabilisation of coordination patterns to cope with the varied demands of walking.

The main role of gait re-training on motor synergy and coordination patterns is to facilitate inter-limb coordination in terms of spatial and temporal organisation. In fact, adjustments of foot contacts in a contralateral fashion (alternate left and right heel contacts) are constrained primarily by environments such as treadmill belt's motion. These adjustments are coordinated with positional and velocity control (as components of CRP) that is the main parameters of movement control in the NMS system (Stergion, 2001). For example, the study by Combs et al. (2013) on body-weight supported treadmill training and inter-limb coordination showed that the paretic and non-paretic side coordination in stroke patients was shifted towards an in-phase pattern and was maintained for 6 months post- intervention. The major changes in gait occurred in the swing phase. Visintin and Barbeau (1994) reported the positive benefits of body-weight supported treadmill training on the stance phase of gait in stroke survivors. These benefits included more symmetrical weight shifts, more symmetrical activation of the tibialis anterior and quadriceps during limb loading, greater stance phase hip extension and a more symmetrical single and double stance ratio. Facilitating adaptations in a motor system to create variant movement patterns, which may be changed due to NMS problems, is paramount in gait re-training interventions (Jeng, et al., 1996; Hamill, et al., 1999; Heiderscheit, et al., 2002).

The studies that have used external cues (Roerdink, et al., 2007) as task constraints showed that acoustically paced treadmill walking, in which patients could hear a sound during heel contact, improved inter-limb coordination in individuals with stroke because it provided a form of auditory-motor coupling during walking. Wagenaar and Beek (1992) and Wagenaar and van Emmerik (1994) suggested that alterations in perception-action coupling by using external rhythmic information could enhance the organisation of pathological movement coordination.

Intra-limb coordination, on other hand, was not as flexible to different task constraints as inter-limb coordination (Combs et al., 2013). Mainly, coordination between joints of adjacent segments is determined by their role in body transfer from stance to swing phases and any lack of coordination, as a form of timing (lag) and position in planes of motion, is largely a task-dependent mechanism (Daly, et al., 2007; Giannini & Perell, 2005; Hutin et al., 2012; Shafizadeh et al., 2013). Another reason for a lack of intra-limb coordination changes following task modifications could be the method of analysis. For example, simplification of multi-segment synergy into a coupled unit (only two segments) in the above-mentioned studies could overlook the complexity and dimensionality of the NMS system (Glazier, Wheat, Pease, & Bartlett, 2006). In addition, there are other methods (e.g. uncontrolled manifold and principal component analysis) for quantification of the multi-segment synergies that provide a better overall picture about the nature of variability and the effect of task experience on development of motor synergies (Latash, 2010; Scholz & Schöner, 1999).

5. Conclusion

This review only considered gait re-training interventions that were related to locomotion tasks. Future review studies could include other relevant, related interventions that could improve walking performance (e.g. resistance training and aquatic exercises).

The results of this review and meta-analysis showed that motor disorder, as a neuromusculoskeletal condition, could change coordination patterns that emerged, either bilaterally or ipsilaterally, in order to adapt to changing task constraints of walking in dynamic environments. In addition, gait re-training interventions that have been used in individuals with motor disorder could provide an opportunity for a motor system to explore variant, functional solutions for better adaptations required in light of physical, perceptual and cognitive constraints on individuals.

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Table 1. Basic characteristics of studies included in systematic review

No	Study	Motor Disorder	Patient	Abled-Body	Coordination Pattern	Gait Setting	Quality Score	Gait re-training
28	Alice et al (2007)	Parkinson's Disease	10	0	Hip-knee	Walkway	5	None
31	Awai &Curt (2014)	Spinal Cord Injury	19	19	Hip-Knee	Walkway	6	Pace (preferred/slow speed
16	Barela et al (2000)	Stroke	6	6	Hip-knee	Walkway	6	None
18	Chiu et al (2010)	Hip arthroplasty	20	10	Hip-knee/ knee-ankle	Walkway	8	None
10	Combs et al (2013)	Stroke	19	22	Inter-limb	Walkway	7	Treadmill training (8-week, 24 sessions, 20-min)
12	Daly et al (2007)	Stroke	15	5	Hip-knee	Walkway	6	Treadmill training (12-week, 48 sessions, 30-min)
11	Fowler et al (2009)	Cerebral Palsy	15	0	Hip-knee	Walkway	5	None
1	Gianni and Perell (2005)	Stroke	11	10	Hip-knee/ knee-ankle	Walkway	5	None
5	Heiderscheit et al (2002)	Pattelofemoral Pain	8	8	Hip-knee/Knee-ankle	Treadmill	6	None
13	Hoogkamer et al (2015)	Cerebellar Ataxia	18	14	Hip-Hip	Walkway	4	None
7	Hutin et al (2011)	Stroke	14	15	Thigh-shank	Walkway	6	None
6	Hutin et al (2012)	Stroke	27	20	Shank-foot/ thigh-shank	Walkway	5	Pace (preferred/maximum speed)
29	Lewek et al (2009)	Stroke	15	0	Hip-knee	Walkway	5	Robot
17	Liu et al (2014)	Osteoarthrtis	30	15	Inter-limb/Intra-limb	Walkway	6	None
21	Meyns et al (2012)	Cerebral Palsy	26	24	Inter-limb	Walkway	6	None
20	Meyns et al (2014)	Cerebral Palsy	15	23	Inter-limb	Walkway	6	None
23	Mian et al (2011)	Parkinson's Disease	12	13	Knee-ankle	Walkway	6	Gait tasks
19	Nanhoie-Mahbier et al (2013)	Parkinson's Disease	14	10	Inter-limb	Treadmill	7	Gait task (split-belt walking)
27	Ornetti et al (2011)	Osteoarthrtis	11	9	Knee-ankle	Walkway	6	None
14	Peterson et al (2012)	Parkinson's Disease	12	10	Inter-limb	Walkway	6	Gait tasks (forward/backward walking)
26	Plotnik et al (2008)	Parkinson's Disease	34	0	Inter-limb	Walkway	6	None
3	Plotnik et al (2009)	Parkinson's Disease	21	13	Inter-limb	Walkway	5	Dual-tasking (number subtraction)
24	Plotnik et al (2011a)	Parkinson's Disease	30	0	Inter-limb	Walkway	7	Dual-tasking
25	Plotnik et al (2011b)	Parkinson's Disease	30	0	Inter-limb	Walkway	5	Dual-tasking(number subtraction)
2	Reynolds, et al (1999)	Huntington's' Disease	6	30	Hip-knee/ knee-ankle	Walkway	6	None
22	Rinaldi et al (2013)	Stroke	10	10	Hip-knee/ knee-ankle	Treadmill	7	Pace (low and high speed walking)
8	Roerdink et al (2007)	Stroke	10	9	Inter-limb	Treadmill	6	Pace (preferred/fast/slow)
32	Serrao et al (2012)	Cerebellar Ataxia	16	15	Hip-knee/Knee-ankle	Walkway	7	None
4	Shafizadeh et al (2013)	Multiple Sclerosis	12	12	Knee-ankle	Treadmill	7	None
9	Stolze et al (2002)	Cerebellar Ataxia	12	12	Hip-knee/ knee-ankle	Treadmill	6	None
30	St-Onge et al (2004)	ACL	6	9	Hip-Knee-Ankle	Walkway	6	None
33	Tanahashi et al (2013)	Parkinson's Disease	20	0	Inter-limb	Walkway	6	None
15	Wang et al (2009)	Osteoarthrtis	15	15	Hip-knee/ knee-ankle	Walkway	6	Gait tasks (different heights of obstacle 10%, 30%)

Table 2. Mean (SD) of groups, ES's and MCID results.

Study	Measure (unit)	Abled-body (Mean)	Abeld-body (SD)	N	Patient (Mean)	Patient (SD)	N	Effect Size [CI]	Normalised SD	Mean Difference	MCID
Chiu et al (2010)	Deviation phase	30.6	7.2	10	41.1	17.9	20	-0.67 [-1.45, 0.11]**	2.91	10.50*	7.59
Combs et al (2013)	Relative phase (deg)	-0.6	6.03	18	-11.45	15.91	15	0.91 [0.19, 1.64]**	2.55	-10.85 *	-13.40
Daly et al (2007)	Coefficient of correpondence (%)	0.97	0.003	5	0.75	0.13	15	1.84 [0.64, 3.03]**	0.02	-0.22	-0.24
Gianni and Perell (2005)	plot area (mm)	158	64.8	10	48	46.1	11	1.89 [0.83, 2.96]**	14.51	-110.00	-124.51
Heiderscheit et al (2002)	Relative phase (deg)	3.8	0.8	8	4.5	1	8	-0.73 [-1.75, 0.29]**	0.21	0.70	0.49
Hoogkamer et al (2015)	Maximum Lyapunov exponent	1.58	0.14	14	1.72	0.16	18	-0.90 [-1.64, -0.16]**	0.04	0.14*	0.10
Hutin et al (2011)	Relative phase (deg)	62.4	6.9	15	61	22.3	14	0.08 [-0.64, 0.81]	3.44	-1.40	-4.84
Hutin et al (2012)	Relative phase (deg)	6.5	1.1	20	18.3	6.3	27	-2.40 [-3.16, -1.63]**	0.92	11.80	10.88
Meyns et al (2012)	Relative phase (deg)	178.9	10.25	24	175.3	14.2	26	0.28 [-0.27, 0.84]**	2.87	-3.60	-6.47
Meyns et al (2014)	Relative phase (deg)	141.6	4.4	23	142.2	10.6	15	-0.08 [-0.73, 0.57]	1.74	0.60	-1.14
Mian et al (2011)	Phase coordination index (%)	8.9	2.3	13	10.8	3.3	12	-0.65 [-1.46, 0.16]**	0.66	1.90*	1.24
Nanhoie-Mahbier et al (2013)	Phase coordination index (%)	4.09	0.43	10	3.96	0.43	14	0.29 [-0.52, 1.11]**	0.11	-0.13*	-0.24
Peterson et al (2012)	Phase coordination index (%)	4.3	1.3	10	7.3	2.5	12	-1.41 [-2.37, -0.45]**	0.44	3.00*	2.56
Plotnik et al (2009)	Phase coordination index (%)	3.24	0.18	13	5.24	0.61	21	-3.95 [-5.16, -2.73]**	0.09	2.00*	1.91
Roerdink et al (2007)	Relative phase difference (deg)	2.1	4.1	9	27.5	7.5	10	-3.95 [-5.63, -2.28]**	1.34	25.40*	24.06
Shafizadeh et al (2013)	Relative phase (deg)	-15.17	2.5	12	-86.6	37.1	12	2.62 [1.48, 3.76] **	5.27	-71.43*	-76.70
St-Onge et al (2004)	Asymmetry index (%)	6.8	1.82	9	8.2	2.74	6	-0.59 [-1.66, 0.47]**	0.53	1.40*	0.87
Wang et al (2009)	Deviation phase	7.92	4.3	15	10.17	6.31	15	-0.41 [-1.13, 0.32]**	1.24	2.25*	1.01

*** Higher score represents a worse coordination pattern**

**** Clinical significant in favour of abnormal pattern**

Note: MCID is calculated by subtracting the mean difference from pooled SD. If the MCID value was positive, there was a clinical significant difference between groups as showed by ** in ES column.

Table 3. Mean (SD) of conditions, ES's and MCID results.

Study	Measure (unit)	Baseline (Mean)	Baseline (SD)	N	Intervention (Mean)	Intervention (SD)	N	Effect Size [CI]	Normalised SD	Mean Difference	MCID
Combs et al (2013)	Relative phase (deg)	-11.45	15.91	15	-9.37	19.49	15	-0.11 [-0.83, 0.60]	4.21	2.08 *	-2.13
Daly et al (2007)	Coefficient of correpondence (%)	0.75	0.13	15	0.77	0.14	15	-0.14 [-0.86, 0.57]	0.03	0.02	-0.01
Hutin et al (2012)	Relative phase (deg)	18.3	6.3	27	16.1	6.3	27	0.34 [-0.19, 0.88]	1.54	-2.20	-3.74
Lewek et al (2009)	Coefficient of correpondence (%)	0.79	0.1	15	0.81	0.1	15	-0.19 [-0.91, 0.52]	0.02	0.02	0.00
Nanhoie-Mahbier et al (2013)	Phase coordination index (%)	3.96	0.43	14	4.96	0.41	14	-2.31 [-3.30, -1.32]**	0.10	1.00*	0.90
Peterson et al (2012)	Phase coordination index (%)	7.3	2.5	12	13.9	3.9	12	-1.95 [-2.95, -0.94]**	0.74	6.60*	5.86
Plotnik et al (2009)	Phase coordination index (%)	5.24	0.61	21	7.71	0.91	21	-3.13 [-4.06, -2.20]**	0.18	2.47*	2.29
Plotnik et al (2011b)	Phase coordination index (%)	5.22	3.23	30	7.63	3.82	30	-0.67 [-1.19, -0.15]**	0.84	2.41*	1.57
Roerdink et al (2007)	Relative phase difference (deg)	23.7	7.3	10	25.9	9.1	10	-0.26 [-1.14, 0.63]**	1.95	2.20*	0.25
Wang et al (2009)	Deviation phase	10.17	6.31	15	9.58	8.08	15	0.08 [-0.64, 0.80]	1.70	-0.59*	-2.29

*** Increased score is worsen the coordination pattern**

**** Clinical significant against intervention**

Note: MCID is calculated by subtracting the mean difference from pooled SD. If the MCID value was positive, there was a clinical significant difference between conditions as showed by ** in ES column.

Table 4. The characteristics of walking interventions in different studies.

Study	Effect Size [CI]		Walking Task	Training Volume
Combs et al (2013)	-0.11 [-0.83, 0.60]		Body-weight support treadmill	24 sessions, 20 min per session
Daly et al (2007)	-0.14 [-0.86, 0.57]		Mixed walking (treadmill,overground)	48 sessions, 1.5hrs per session
Hutin et al (2012)	0.34 [-0.19, 0.88]		Walking with normal and fast pace	3 trials, 6m walking
Lewek et al (2009)	-0.19 [-0.91, 0.52]		Robotic locomotor	12 sessions, 30 min per session
Wang et al (2009)	0.08 [-0.64, 0.80]		Obstacle crossing with different heights	6 trials, obstacle crossing steps
Nanhoie-Mahbier et al (2013)	-2.31 [-3.30, -1.32]	*	Split-belt treadmill	1 trial, 2 min
Peterson et al (2012)	-1.95 [-2.95, -0.94]	*	Forward-backward walking	5-8 trials, 10m walking distance
Plotnik et al (2009)	-3.13 [-4.06, -2.20]	*	Cognitive dual-task during walking	1 trial, 2 min self-selected pace
Plotnik et al (2011)	-0.67 [-1.19, -0.15]	*	Cognitive dual-task during walking	1 trial, 80m walking distance
Roerdink et al (2007)	-0.26 [-1.14, 0.63]	*	Walking with normal and fast pace	1 trial per condition, 90 sec

*** Clinical significant change**

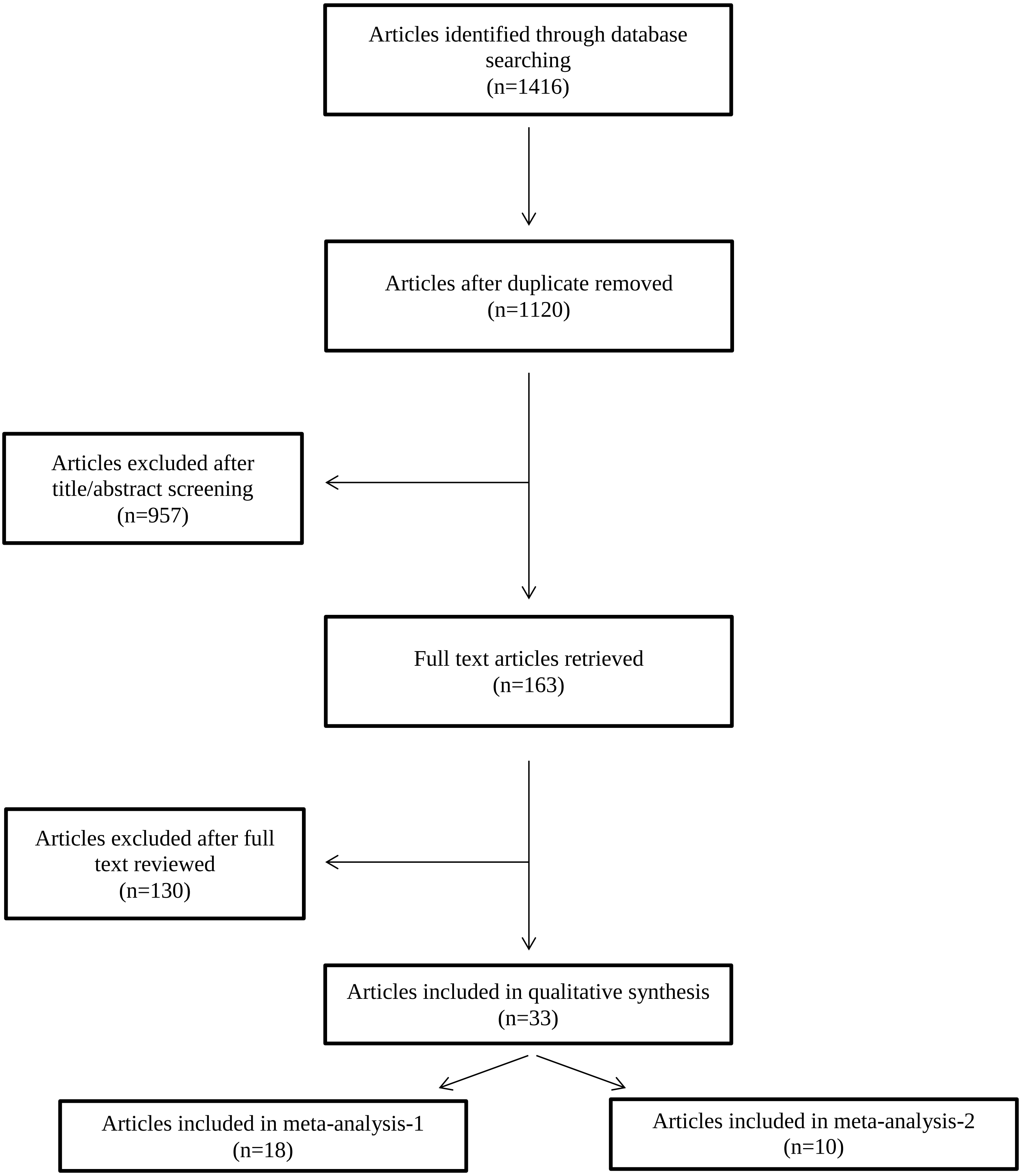

Figure 1. Flow diagram of selection of studies focusing on limb coordination during walking

Study or Subgroup	Std. Mean Difference IV, Random, 95% CI
Chiu et al (2010)	-0.67 [-1.45, 0.11]
Combs et al (2013)	0.91 [0.19, 1.64]
Daly et al (2007)	1.84 [0.64, 3.03]
Gianni and Perell (2005)	1.89 [0.83, 2.96]
Heiderscheit et al (2002)	-0.73 [-1.75, 0.29]
Hoogkamer et al (2015)	-0.90 [-1.64, -0.16]
Hutin et al (2011)	0.08 [-0.64, 0.81]
Hutin et al (2012)	-2.40 [-3.16, -1.63]
Meyns et al (2012)	0.28 [-0.27, 0.84]
Meyns et al (2014)	-0.08 [-0.73, 0.57]
Mian et al (2011)	-0.65 [-1.46, 0.16]
Nanhoie-Mahbier et al (2013)	0.29 [-0.52, 1.11]
Peterson et al (2012)	-1.41 [-2.37, -0.45]
Plotnik et al (2009)	-3.95 [-5.16, -2.73]
Roerdink et al (2007)	-3.95 [-5.63, -2.28]
Shafizadeh et al (2013)	2.62 [1.48, 3.76]
St-Onge et al (2004)	-0.59 [-1.66, 0.47]
Wang et al (2009)	-0.41 [-1.13, 0.32]
Total (95% CI)	**-0.24 [-0.44, -0.04]**

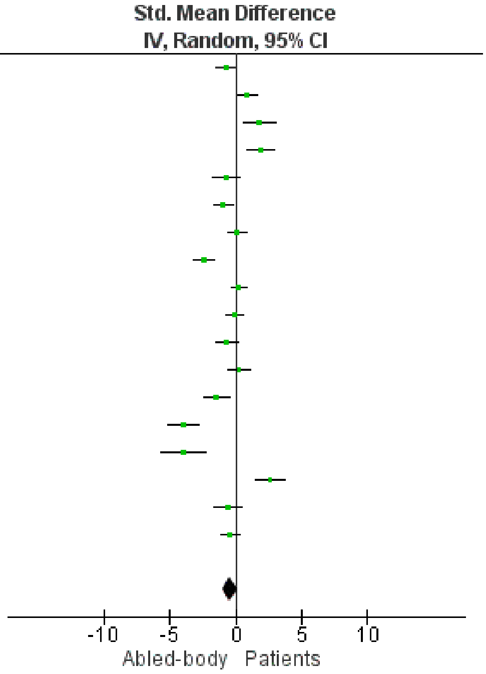

Figure 2. Forest plot comparing the limb coordination during walking between patients and abled-body groups.

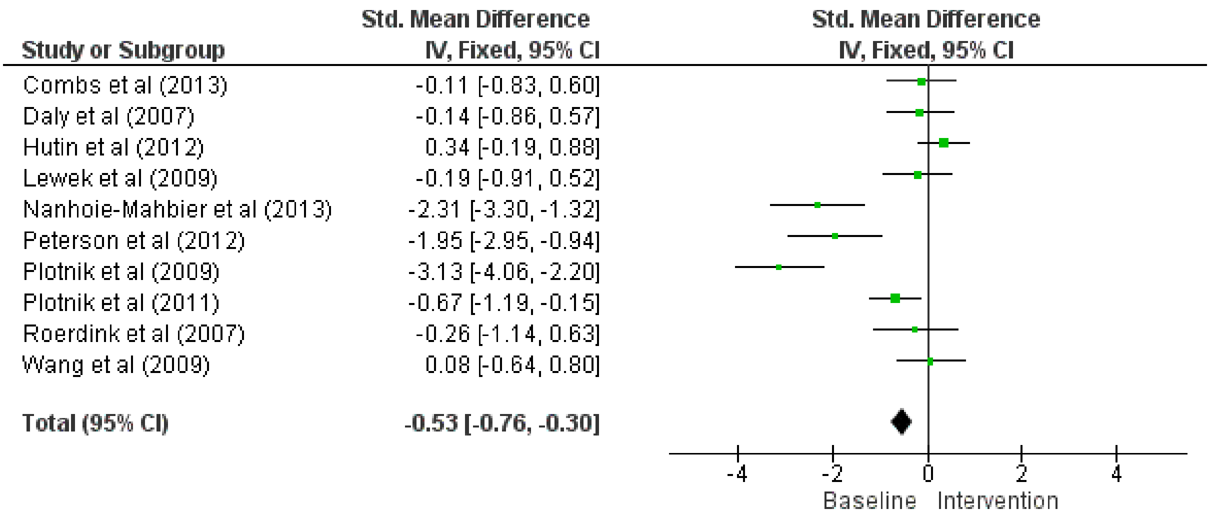

Figure 3. Forest plot comparing the limb coordination during walking between baseline and intervention conditions.