Spatial-Temporal Gait Characteristics in Individuals With Hip Osteoarthritis: A Systematic Literature Review and Meta-analysis

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Spatial-Temporal Gait Characteristics in Individuals With Hip Osteoarthritis: A Systematic Literature Review and Meta-analysis

Osteoarthritis (OA) of the hip is a progressive musculoskeletal condition affecting approximately 7% of the general population. There is no cure for OA, which clinically culminates in total hip replacement. In Australia alone, there were 332 351 hip replacements performed from 1999 to 2011, with almost 90% being due to OA. Hip OA is associated with pain, stiffness, and functional limitation, the extent of which depends on the amount of structural disease progression and associated symptoms, as well as sensorimotor adaptations to the disease. Management of hip OA is therefore complex and requires an understanding of the presenting symptoms and functional limitations of the individual. The primary management goals in hip OA are to minimize pain, maximize function, and limit the rate of structural disease progression in those with the condition. Given that walking is an integral and frequent activity of daily living and an exercise commonly prescribed to persons with hip OA, it is important to understand how hip OA influences gait characteristics to inform effective management of the disease.

Spatial-temporal gait parameters are a simple way of objectively assessing gait dysfunction and monitoring treatment progress in a clinical setting. Spatial-temporal gait parameters can be measured using a variety of methods, from simple clinical approaches requiring only a stopwatch and tape measure to more complex approaches using light gates, instrumented walkways, and/or motion-capture systems. Self-selected gait speed, which is a function of stride length and stride time (or cadence), is a common measure of walking speed and is a good indicator of gait function. In individuals with hip OA, walking speed is generally reduced compared to healthy controls, with a slower speed and greater gait asymmetry. However, the extent of gait dysfunction can vary widely among individuals with hip OA, and there is a need for a more comprehensive understanding of the factors that influence gait in this population. 

STUDY DESIGN: Systematic literature review and meta-analysis. 

OBJECTIVE: To systematically review and critically evaluate the literature to determine how basic gait characteristics are altered in individuals with hip osteoarthritis (OA).

BACKGROUND: Hip OA is a progressive musculoskeletal condition that leads to pain, stiffness, and functional limitation in activities such as walking. Understanding gait dysfunction in people with hip OA may contribute to more effective management of the disease.

METHODS: Eleven electronic research databases were searched. Studies comparing basic gait parameters in individuals with hip OA to healthy controls and the affected to the contralateral limb of individuals with hip OA were included. The studies were critically appraised for methodological quality. Available data were extracted, and meta-analysis was performed, with standardized effect sizes (Cohen d) and corresponding 95% confidence intervals computed for gait speed, cadence, step and stride length, stance, swing and double-stance duration, and step width.

RESULTS: The final analysis included 30 articles. Self-selected gait speed was 26% slower in individuals with hip OA relative to controls, which was explained by shorter stride length. Consistent evidence was found for greater symmetry in individuals with hip OA than controls, with shorter step length and stance duration in the affected compared to the contralateral limb.


KEY WORDS: ambulation, gait speed, step, stride, walking

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spatial-temporal variable that is considered to be a primary measure of overall gait function.\textsuperscript{7} Reductions in self-selected gait speed are documented in those with knee OA\textsuperscript{8,9,10} and older compared to younger adults,\textsuperscript{11,12} and would be expected to occur with hip OA.

OA is a known risk factor for falls,\textsuperscript{13} and so it is important to understand how OA influences gait stability. Increased step width may be interpreted as an attempt to improve stability in the frontal plane and has been reported in older compared to younger adults.\textsuperscript{8,14} Similarly, increased double-support time, as observed in frail gait,\textsuperscript{15} may indicate an attempt to decrease the proportion of the gait cycle occurring in single stance, at which time the base of support is smallest and stability is lowest.\textsuperscript{16} Furthermore, comparisons of spatial-temporal gait parameters, such as stance time and step length compared between the left and right sides, can provide information about gait symmetry, which may be altered in those with hip OA because of increased pain, muscle weakness, and other sensorimotor deficits in the more affected limb.

The purpose of this systematic review, critical evaluation and meta-analysis of the literature was to determine how basic spatial-temporal gait characteristics related to speed, stability, and symmetry are altered in individuals with unilateral hip OA. The findings of this review will improve characterization of the functional deficits in those with hip OA and provide objective evidence to inform clinical management of hip OA.

METHODS

Inclusion Criteria

The studies included in this review were original research (eg, cross-sectional studies or randomized controlled trials) that reported comparisons of 1 or more spatial-temporal gait parameters between the affected limb versus the contralateral limb in individuals with unilateral hip OA, or the affected limb in those with unilateral hip OA versus the matched limb in healthy controls. Only studies written in English were included.

Literature Search Strategy

Eleven database searches were undertaken by 1 reviewer (M.C.) during March 2013. These databases were Ausport-Med (via Informit), CINAHL (via EBSCOhost), Cochrane Library (Cochrane Reviews, DARE, and Cochrane Central Register of Controlled Trials), Embase (via Ovid), Inspec (via Web of Knowledge), MEDLINE (via Ovid), PsyclINFO (via Ovid), SPORTDiscus, ScienceDirect (via Elsevier), and Web of Science (via Web of Knowledge). Searches were performed using the combined and/or truncated key terms: (walk* OR gait OR locomot* OR ambulat* OR biomechanic*) AND (speed* OR velocit* OR cadence OR ‘step length’ OR ‘stride length’ OR stance OR swing OR spatial-temporal OR spatial OR temporal OR spatial-temporal) AND (“arthriti* OR *arthrosis OR arthroplast* OR replacement*) AND (hip OR femor* OR coxa* OR femur*) NOT (fracture* OR Perthes OR amputee OR orthoses OR orthotic OR Rheumat*)

Data Extraction and Analysis

Data extraction was undertaken by 1 reviewer (M.C.). Participant characteristics (sample size, age, sex, and structural and functional severity of hip OA) and study characteristics (walking surface, gait speed, footwear, gait-analysis instrumentation, and whether gait data were adjusted for height) were extracted from each study. Means and standard deviations for each outcome measure were extracted, and standardized effect sizes (Cohen $d$) and corresponding 95% confidence intervals (CIs)\textsuperscript{20} were calculated. Standardized effect sizes are dimensionless and take account of differences between studies in the units of the original measurement. Data were grouped into the following categories of related measures: (1) gait speed (speed, cadence, and stride and step length), (2) gait stability (stance, swing and double-support duration, and step width), and (3) gait symmetry (step length and stance and swing duration), and presented as forest plots to facilitate visual comparison of findings between individuals with hip OA and control groups and between the affected and contralateral limbs of those with hip OA. Where spatial-temporal gait parameters were reported across a range of conditions in a given study (eg, different gait speeds), a single studywise effect size was calculated using a fixed-effects model, in
which the conditionwise effect sizes were weighted by the inverse of their variances. Data for self-selected and fixed gait speeds were reported on separate forest plots. If tabulated data required to calculate effect sizes were not available in the original article, these data were requested from the author(s) or digitized from figures in the original article. Overall pooled effect sizes, 95% CIs, and heterogeneity statistics ($I^2$) were calculated for each spatial-temporal parameter using a fixed-effects model, in which effect sizes from individual studies were weighted by the inverse of their variances. The level of heterogeneity ($I^2$) was categorized as low (25%), moderate (50%), and high (75%). Mode of walking (overground or treadmill) is known to influence spatial-temporal gait characteristics in older persons. Post hoc sensitivity analyses were conducted to assess whether the findings were robust with respect to mode of walking by recalculating overall pooled effect sizes, 95% CIs, and heterogeneity statistics ($I^2$) from overground-walking data only, where applicable.

### Results

#### Yield

The initial search yielded 3263 articles, and subsequent manual searches revealed a further 10 articles. Of the 122 articles that met the preliminary inclusion criteria based on title and abstract, 45 met the overall inclusion criteria to be assessed for methodological quality and data extraction. In 10 articles, data were not available or able to be extracted for analysis, and in 4 articles the required data were not available. Attempts to obtain the data from the authors were unsuccessful, and these 10 articles were excluded from the review. Three conference proceedings reported data identical to those published elsewhere by the same group of authors and were excluded. A further 4 articles that reported spatial-temporal gait data for the same cohort of participants were combined, leaving a final yield of 30 studies.

#### Methodological Quality Appraisal

The included studies exhibited good methodological quality, with a mean ± SD reviewers’ quality appraisal score of 8.3 ± 1.1 (range, 6.5-11.5) from a potential maximum score of 12 (TABLE 1, available online). The worst scores were for items 11 and 12, which attempt to determine whether the study participants were representative of the entire population. No studies were excluded on the basis of the quality appraisal. The Cohen kappa values

![Flow chart (FIGURE 1)](image-url)
for the level of agreement in methodological quality scores between the 2 reviewers for each item ranged from 0.36 to 1.0 (TABLE 1, available online). With the exception of item 12 (κ = 0.36), the level of agreement was greater than or equal to 0.61.

**Characteristics of Included Studies**

Characteristics of the included studies are summarized in TABLE 2 (available online). There were 821 hip OA and 519 control participants across all 30 studies. Twenty-five of 30 studies included hip OA and control groups, whereas the remaining 5 studies included only participants with hip OA. The age of participants with hip OA ranged from 20 to 85 years across all 30 studies. The participants with hip OA consisted solely of women in 8 studies and the sex of participants with hip OA was not reported in 1 study; the participants in the remaining 21 studies consisted of both men and women. Age and sex characteristics of control groups were closely matched to those with hip OA in most studies.

Severity of hip OA was determined from plain radiographs in 9 studies. Hip OA severity was not reported in 17 studies, 15 of which stated that the participants were scheduled to undergo a total hip replacement. Severity of hip OA was not defined in 4 studies.

Clinical symptoms were reported in 19 studies, of which 11 studies defined symptomatic hip OA based on the presence of pain. 7 studies used the Harris hip score to classify disease severity, and 1 study used both pain and Harris hip score in the disease classification. The remaining 11 of the 30 studies did not report clinical symptoms. Only 6 studies reported both radiographic hip OA severity and the presence of clinical symptoms and/or functional limitations in participants.

Walking trials were performed over-ground in 21 studies, on a treadmill in 7 studies, and on both surfaces in 2 studies. Eighteen studies assessed self-selected preferred (normal) gait speed over-ground and 1 study on a treadmill; 2 studies reported self-selected preferred (normal) and fast gait speeds over-ground; 1 study reported on self-selected slow, preferred (normal), and fast gait speeds over-ground; and 2 studies did not report the gait speed tested over-ground. Seven studies had participants walk at a fixed absolute gait speed on a treadmill. Participants performed walking trials barefoot in 9 studies and were shoed in 3 studies.

<p>| A. Walking Speed (Self-Selected) |</p>
<table>
<thead>
<tr>
<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA &lt; Control</th>
<th>Hip OA &gt; Control</th>
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</thead>
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<tr>
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<td>9</td>
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<td>-</td>
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<td>Chiu et al¹²</td>
<td>20</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fang et al²¹</td>
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<td>25</td>
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<td>Hurwitz et al²²</td>
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<td>21</td>
<td>-</td>
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<td>Kiss⁴³</td>
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<td>10</td>
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<td>Kyriazis⁵⁰</td>
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<td>Lugade et al²⁷</td>
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<td>9</td>
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<tr>
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<td>30</td>
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<tr>
<td>Tanaka et al⁴³</td>
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<td>26</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Watanabe et al⁵⁰</td>
<td>30</td>
<td>54</td>
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<td>Watelain et al⁵¹</td>
<td>17</td>
<td>17</td>
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<td>-</td>
</tr>
<tr>
<td>Pooled I² = 92%</td>
<td>479</td>
<td>343</td>
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</table>

Abbreviation: OA, osteoarthritis.

<p>| B. Cadence at Self-Selected Walking Speeds |</p>
<table>
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<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA &lt; Control</th>
<th>Hip OA &gt; Control</th>
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<td>Fang et al²¹</td>
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<td>Hurwitz et al²²</td>
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<td>Illyés and Kiss⁴³</td>
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<td>Klausmeier et al⁴⁵</td>
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<td>Watelain et al⁵¹</td>
<td>17</td>
<td>17</td>
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<td>-</td>
</tr>
<tr>
<td>Pooled I² = 92%</td>
<td>268</td>
<td>238</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pooled I² = 89%*</td>
<td>257</td>
<td>217</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviation: OA, osteoarthritis.

* Treadmill walking.

FIGURE 2. Continues on page 295.
whereas footwear was not discussed in the remaining 18 studies.

Spatial-temporal gait parameters were assessed using 3-D motion capture in 23 studies, force plates in 1 study, in-shoe pressure sensors in 2 studies, tape measure and stopwatch in 2 studies, and a conductive walkway with telemetry in 2 studies. Gait parameters were adjusted for participant height in 7 studies.

**Additional Analysis**

Step length and stance-phase duration data from 1 study were digitized from graphs. The pooled mean and standard deviation for spatial-temporal data across 2 groups of individuals with preoperative hip OA in 2 studies, and 4 across test-retest of individuals with hip OA conditions in 2 studies, and across 2 groups of individuals with hip OA in 1 study were used in the meta-analysis. In the control groups, the within-study pooled mean and standard deviation for relevant gait measures across dominant and nondominant lower limbs were used in 8 studies. In 4 studies, the swing duration for each limb was calculated in seconds from the reported single-support duration (as percentage of gait cycle) of the opposite limb. The contralateral single-limb support time equals the swing phase of the opposite limb. In 1 study, the swing duration originally reported as percentage of gait cycle was calculated from given values of the contralateral single-limb support time in seconds. Stride length was calculated as a function of cadence and speed in the studies by Reininga et al. and Watanabe et al., whereas cadence was calculated as a function of stride length and cadence in 1 study. Where studies reported values for both limbs in individuals with hip OA and in controls, symmetry indices were calculated. Symmetry indices for step length and swing duration were calculated from the ratio of the difference between mean values computed across both limbs for groups of individuals with hip OA and controls at fixed treadmill walking speeds in 7 studies. A symmetry index of zero indicates perfect symmetry between limbs, whereas a positive symmetry index indicates a greater value for the contralateral or dominant leg compared with the affected or the nondominant leg, respectively.

**Gait Speed–Related Measures**

Overall, hip OA had a large negative effect on self-selected gait speed, with slower self-selected gait speeds reported in individuals with hip OA relative to controls while walking overground in 16 of 17 studies. The effect of hip OA on self-selected gait speed was highly heterogeneous; across the 17 studies, the mean ± SD self-selected gait speed was 26.1% ± 20.9% slower for the individuals with hip OA (mean ± SD speed, 0.95 ± 0.19 m/s) than it was in controls (1.29 ± 0.33 m/s).

There was a moderate but highly heterogeneous negative effect of hip OA on cadence at self-selected walking speeds, with 5 of 11 studies reporting slower mean cadence in individuals with hip OA relative to controls (Figure 2B). Exclusion of the single treadmill study via sensitivity analysis resulted in an effect size change of −0.1 but no discernible effect on heterogeneity between studies.

Stride length at self-selected walking speeds was shorter for individuals with hip OA than controls in all 11 studies (Figure 2C), which were all overground-walking studies. Overall, hip OA had a large but highly heterogeneous negative effect on stride length.

Individuals with hip OA had a shorter step length of the affected limb than controls in all 10 self-selected walking-speed studies (Figure 3A). Overall, hip OA had a large but highly heterogeneous negative effect on step length of the affected limb. Exclusion of the single treadmill-walking study had no marked effect on effect size or heterogeneity between studies.

Step length of the contralateral limb of individuals with hip OA was greater than

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**FIGURE 2 (CONTINUED).** Normalized effect sizes, 95% confidence intervals, and sample sizes for studies comparing (A) self-selected walking speed, (B) cadence, and (C) stride length at self-selected walking speeds between individuals with hip osteoarthritis and control participants. The pooled effect size and its 95% confidence interval and the homogeneity statistic (I²) were calculated using a fixed-effects model, where individual study results were weighted by the inverse of their variance. For those studies that reported spatial-temporal gait data across multiple conditions, study-wise pooled effect sizes and 95% confidence intervals, weighted by the inverse of the variance of condition-wise effect sizes, were calculated and used in the calculation of pooled effect sizes and homogeneity statistics.

**Abbreviation:** OA, osteoarthritis.
it was in controls in both overground studies, but less than it was in controls in 1 treadmill-walking study at self-selected walking speeds (FIGURE 3B). Overall, there was a large positive but highly heterogeneous effect of hip OA on the step length in both affected and contralateral limbs.

**Gait Stability–Related Measures**

At self-selected walking speeds, stance duration was greater in the affected limb of individuals with hip OA than in healthy control limbs for all 4 studies (FIGURE 5A). Overall, there was a small positive effect of hip OA on stance duration of the affected limb of individuals with hip OA compared to the limbs of healthy controls, with no heterogeneity between the studies.

At self-selected walking speeds, swing duration was shorter in individuals with hip OA than in controls for both the affected and contralateral limbs (FIGURES 5B and 5C, respectively). Overall, the results suggest a large negative but highly heterogeneous effect on swing duration in both limbs of those with hip OA compared to healthy controls. Exclusion of a single treadmill-walking study from the pooled analyses resulted in effect-size changes of approximately 0.1 and –0.3 in the affected and contralateral limbs, respectively, but had little effect on heterogeneity between studies.

Double-support duration was greater in the affected limb of individuals with hip OA compared to controls at self-selected walking speeds in all 6 studies (FIGURE 6A). Overall, there was a large positive but highly heterogeneous effect of hip OA on double-support duration of the affected limb. Exclusion of a single treadmill-walking study from the pooled analyses resulted in an effect-size change of approximately –0.1 but had no effect on heterogeneity between studies.

Double-support duration was greater for the contralateral limb of individuals with hip OA relative to controls at self-selected walking speeds in 2 of 2 studies (FIGURE 6B). Overall, there was a large positive effect of hip OA on double-support duration of the contralateral limb of individuals with hip OA, with no heterogeneity.
between the overground-walking studies.

Step width on the affected limb of individuals with hip OA was greater than that of controls in 4 of 5 studies at self-selected walking speeds (FIGURE 6C). Overall, there was a moderate positive effect of hip OA on step width of the affected limb, with moderate heterogeneity between studies. Exclusion of a single treadmill-walking study from the pooled analyses resulted in an effect-size change of approximately −0.2 and no heterogeneity between studies.

Step width for the contralateral limb of individuals with hip OA at self-selected walking speeds was reported by 1 treadmill study to be smaller than that of the control group (FIGURE 6D).

Swing duration at fixed walking speeds was shorter in the affected limb of individuals with hip OA compared to controls in 4 of 6 studies (FIGURE 7A, available online). Overall, there was a small negative effect and low heterogeneity of hip OA on affected limb swing duration for individuals with hip OA compared to controls.

On the other hand, longer swing duration was reported at fixed walking speeds for the contralateral limb of individuals with hip OA compared to controls in 5 of 6 studies (FIGURE 7B, available online). Overall, there was a moderate positive effect, with a moderate level of between-study heterogeneity, of hip OA on contralateral swing duration.

There was consistent evidence for shorter double-support duration for the affected limb of individuals with hip OA compared to controls in all 6 fixed-walking-speed studies (FIGURE 8A, available online). Overall, there was a large negative effect of hip OA on double-support duration, with moderate heterogeneity between studies.

Step width of the affected limb in individuals with hip OA was greater than that of controls in all 5 fixed-walking-speed studies (FIGURE 8B, available online). Overall, there was a large positive but highly heterogeneous effect of hip OA on affected-limb step width.

Similarly, at fixed walking speeds, there was greater step width for the contralateral limb of individuals with hip OA relative to controls in all 4 studies (FIGURE 8C, available online). Overall, there was a large positive, albeit highly heterogeneous, effect of hip OA on step width of the contralateral limb in individuals with hip OA.
Gait Symmetry–Related Measures

At self-selected walking speeds, step length in the affected limb compared to the contralateral limb in individuals with hip OA was shorter in 5 of 8 studies and greater in 3 of 8 studies (FIGURE 9A). Overall, there was a large negative but highly heterogeneous effect of hip OA on step length. Exclusion of 2 treadmill-walking studies from the pooled analysis had little effect on the overall pooled effect size or heterogeneity between studies.

Shorter stance duration in the affected limb compared to the contralateral limb of individuals with hip OA was reported by all 3 studies at self-selected walking speeds (FIGURE 9B). Overall, there was a moderate, albeit with moderate heterogeneity, effect of hip OA on stance duration of the affected limb compared to the contralateral limb of individuals with hip OA. Exclusion of 1 treadmill-walking study from the pooled analysis resulted in an effect-size change of 0.1 and low heterogeneity between studies.

Swing duration of the affected limb was greater than that of the contralateral limb in individuals with hip OA at self-selected walking speeds (FIGURE 9C). There was an overall large positive effect of hip OA on swing duration of the affected limb of individuals with hip OA, but there was high heterogeneity between studies. Exclusion of 1 treadmill-walking study from the pooled analysis resulted in an effect-size change of 0.2, with minimal change in heterogeneity between studies.

At fixed walking speeds, all 6 studies reported shorter step length in the affected limb than for the contralateral limb of individuals with hip OA across a range of speeds (FIGURE 10A, available online). Overall, there was a large negative effect of hip OA on step length of the affected limb, with no heterogeneity between studies.

Swing duration was shorter for the affected limb compared to the contralateral limb of individuals with hip OA in all 6 fixed-walking-speed studies (FIGURE 10B, available online). Overall, there was a moderate negative but highly heterogeneous effect of hip OA on swing duration of the affected limb.

The mean ± SD symmetry index for step length was 8.4 ± 2.8 for individuals with hip OA and 3.2 ± 3.8 for the control group at fixed treadmill-walking speeds. Overall, there was a large negative effect of hip OA on the step-length symmetry index (pooled effect size, 2.19; 95% CI: 1.73, 2.64) computed from 7 studies.

The mean ± SD symmetry index for swing duration was 11.7 ± 8.6 for the individuals with hip OA and 4.9 ± 2.9 for the control group at fixed treadmill-walking speeds. Overall, there was a large negative effect of hip OA on the swing duration symmetry index (pooled effect size, 2.68; 95% CI: 2.26, 3.11) computed from 7 studies.

**DISCUSSION**

This systematic review identified 30 articles that evaluated basic characteristics related to gait speed, gait stability, and gait symmetry in individuals with unilateral hip OA. Overall, the findings of this review confirmed the presence of gait adaption in hip OA, most notably in terms of reduced self-selected gait speed and reduced gait symmetry.

The mean self-selected gait speed in 17 studies for the hip OA group was 0.95 m/s, which was 26% lower than that of the control group (1.29 m/s). Our findings are also consistent with an earlier review that reported 16% slower gait speeds in those with hip OA across 6 studies, and are indicative of gait dysfunction in those with hip OA. The functional significance of this finding is highlighted by the fact that pedestrian crossings are designed for a walking speed of 1.2 m/s. Activities requiring faster gait speeds, such as crossing the road, may therefore be challenging and unsafe for a person with hip OA. Based on data from 6 studies, the observed reduction in self-selected gait speed in hip OA was primarily explained...
by reductions in stride length of the affected limb. In turn, the shorter stride length in hip OA appears to be explained by reductions in step length on the affected side, although this may be offset to some extent by a greater step length of the contralateral limb relative to controls, as reported in 2 of 3 studies. Similar to knee OA and elderly gait, taking shorter but quicker steps appears to be a strategy used in those with hip OA to obtain a given gait speed.

Gait speed, temporal parameters, and sagittal plane spatial parameters are all interrelated. It is therefore difficult to interpret the findings from our review for stance duration, swing duration, double-support duration, and step width at self-selected gait speeds, because they are likely biased by differences in self-selected gait speed between hip OA and control groups. For example, it is possible that the overall trend for shorter swing and longer double-support duration could be confounded by the slower self-selected gait speed in individuals with hip OA alone. In contrast, findings from 6 studies at fixed gait speeds revealed consistent evidence for shorter double-support duration and greater step width in individuals with hip OA compared to controls. The period of double support is considered to be the most stable period of the gait cycle and the period in which adjustments to posture are most easily made. The longer double-support duration in self-selected gait speeds in individuals with hip OA compared to controls may reflect an attempt to increase gait stability during overground walking and subsequently reduce the risk of falling. Conversely, the lesser double-support duration at fixed gait speeds in individuals with hip OA compared with controls likely reflects an attempt to maintain the prescribed treadmill gait speed, which may lead to gait instability. In contrast, the greater step width and, therefore, wider base of support in participants with hip OA compared to controls at both self-selected overground and fixed treadmill gait speeds may be a strategy to increase mediolateral gait stability, albeit at the likely cost of reduced gait efficiency.

Consistent evidence from 6 studies of asymmetry in those with hip OA was also identified, with reduced step length and swing duration in the affected compared to the contralateral limb when walking at fixed speeds on a treadmill and reduced step length at self-selected gait speeds. The large negative effect size (greater than 2) for symmetry index reported in 7 studies, together with the finding that the symmetry index for the hip OA group was more than double that of the controls in both step length and swing duration, provides further evidence for the presence of gait asymmetry in individuals with hip OA. While gait asymmetry may reflect altered stride characteristics of either limb, the findings of this review suggest that, at least for step length, asymmetry in hip OA when walking at fixed speeds results primarily from a decrease in affected-limb step length rather than an increase in step length of the contralateral limb. Gait asymmetry has been reported to remain after the alleviation of pain through total hip arthroplasty, suggesting that neuromuscular dysfunction may contribute to this asymmetry with hip OA and not just pain per se.

Early clinical intervention to address the deficits in gait function identified in the present review may be associated with improved long-term outcomes in individuals with hip OA, even following total hip replacement. The importance of maintaining gait function in the presence of hip OA is illustrated by the finding that gait function prior to total hip replace-
A. Step Length at Self-Selected Walking Speeds

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Abbreviation: OA, osteoarthritis.
*Treadmill walking.

B. Stance Duration at Self-Selected Walking Speeds

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Abbreviation: OA, osteoarthritis.
*Treadmill walking.

C. Swing Duration at Self-Selected Walking Speeds

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Abbreviation: OA, osteoarthritis.
*Treadmill walking.

FIGURE 9. Normalized effect sizes, 95% confidence intervals, and sample sizes for studies comparing (A) step length, (B) stance duration, and (C) swing duration at self-selected walking speeds between affected and contralateral limbs of individuals with hip osteoarthritis. The pooled effect size and its 95% confidence interval and the homogeneity statistic (\(I^2\)) were calculated using a fixed-effects model, where individual study results were weighted by the inverse of their variance. For those studies that reported spatial-temporal gait data across multiple conditions, study-wise pooled effect sizes and 95% confidence intervals, weighted by the inverse of the variance of condition-wise effect sizes, were calculated and used in the calculation of pooled effect sizes and homogeneity statistics.

ment is positively correlated with gait function 12 months following surgery.\(^{25}\) Future consideration should be given to determining if the gait adaptations in speed or symmetry observed in hip OA are primarily compensations directed to reducing pain and/or reflect reported deficits in sensorimotor function in hip OA.\(^{52,66,71}\) An improved understanding of the neuromuscular and biomechanical factors affecting gait speed, mediolateral stability, and symmetry in hip OA may bring about improvements in management of the disease through better targeted exercise programs.

A number of issues identified in the methodological quality assessment undertaken as part of this review should be considered when interpreting the findings of this review and planning future studies. The most important limitation of this review and meta-analysis is the heterogeneity between studies in mode of walking (overground or treadmill), participant characteristics, data collection, and analysis procedures used to quantify spatial-temporal parameters. Walking mode (overground or treadmill) is known to affect the spatial-temporal patterns of older persons.\(^{60}\) Consequently, the post hoc sensitivity analyses that excluded treadmill studies yielded small differences in the pooled effect sizes (range, \(-0.3\) to \(0.2\)), indicating minimal effect of walking mode on these spatial-temporal parameters. The inconsistencies in the heterogeneity (\(I^2\)) changes after the post hoc sensitivity analyses suggest that other factors may be contributing to the heterogeneity between studies. Many studies used participants who were a sample of convenience rather than representative of the entire population. The external validity of future studies could therefore be improved through more widespread recruitment procedures, as this would avoid potential bias that may result from recruiting participants from a single clinic. Interpretation of individual studies and synthesis with the greater literature would also be improved through consistency in
the description of key participant characteristics (eg, whether OA severity was defined using functional and/or radiographic scales, whether the disease is unilateral or bilateral, symptomatic versus non-symptomatic, and the presence/absence of comorbidities such as knee OA). Comparisons of spatial-temporal parameters between individuals with hip OA and controls in the included studies were also often confounded by observed differences in self-selected gait speed, with only a small number of studies comparing spatial-temporal parameters at the same gait speed. It is therefore recommended that future studies control for differences in gait speed between groups. This could be achieved statistically through the inclusion of gait speed as a covariate, experimentally by making direct comparisons between groups at a fixed gait speed, or through appropriate prediction methods. These recommendations are also important for interpreting adaptations in other gait parameters, such as joint kinematics and moments, in those with hip OA. In general, other potentially confounding variables, such as the walking surface (treadmill versus overground), footwear (barefoot versus shod), and participant height and sex, should also be considered, together with the possible influence of different data-collection procedures (3-D motion capture versus instrumented walkways, and single- versus split-belt treadmills) and data-analysis procedures (definitions of spatial-temporal parameters and normalization procedures). In addition, while this review focused on mean double-support durations and step widths of individual participants as measures of gait stability, the stride-to-stride variability of these and other spatial-temporal parameters may provide additional insight into the effect of hip OA on gait stability. Finally, the majority of studies reported only a subsample of the possible spatial-temporal parameters, which made it difficult to understand how related spatial-temporal parameters interact. For example, although most studies reported gait speed, only a small proportion reported corresponding step/stride lengths, cadence, and stride duration. Similarly, only a small number of studies reported spatial-temporal parameters that describe limb symmetry or that potentially relate to a person’s stability during gait. It is therefore recommended that reporting of spatial-temporal parameters, where relevant, be more comprehensive so that interrelations between the parameters can be more thoroughly understood. The spatial-temporal parameters reported in this review could serve as a guide in this respect.

**CONCLUSION**

**OVERALL FINDINGS INDICATE THE** presence of gait adaptation in hip OA, most notably in terms of reduced self-selected gait speed and reduced gait symmetry. Efforts to improve gait function in hip OA should focus on addressing these deficits. Gait speed and gait symmetry may be useful measures for assessing the extent of gait dysfunction and monitoring treatment progress in the clinical environment.

**KEY POINTS**

**FINDINGS:** This review identified consistent evidence for a slower self-selected gait speed and gait asymmetry between the affected and contralateral limbs in persons with unilateral hip OA compared to healthy controls.

**IMPLICATIONS:** The overall findings of this study imply that simple spatial-temporal measures of gait speed and gait symmetry are sensitive to hip OA and thus may have clinical utility in the objective evaluation of gait in individuals with hip OA. **CAUTION:** The generalizability of findings from this review is limited to some extent by differences between included studies in terms of participant characteristics, the type of locomotion investigated, gait speed, the spatial-temporal parameters reported, and methods for collecting and analyzing gait data.

**REFERENCES**


11. Chiu SL, Chou LS. Altered inter-joint coordination during walking in patients with total hip arthroplasty. 34th Annual Meeting of the American Society of Biomechanics; August 18-21, 2010; Providence, RI.


## ONLINE TABLES

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*Items based on Downs and Black. Criterion fully met, 1; criterion partially met, 0.5; criterion not met, 0. Items: 1, the hypothesis/aim/objective of the study is clearly described; 2, the main outcomes to be measured are clearly described in the Introduction or Methods section; 3, the characteristics of participants included in the study are clearly described; 6, the main findings of the study are clearly described; 7, the study provides estimates of random variability in the data for the main outcomes (in nonnormally distributed data, the interquartile range of results and, in normally distributed data, the standard error/deviation or confidence intervals are reported); 10, actual probability values for the main outcomes are reported (eg .035 rather than less than .05, except where P=.001); 11, the participants asked to participate are representative of the entire population from which they were recruited; 12, the participants prepared to participate are representative of the entire population from which they were recruited; 16, clear indication if any of the results of the study are based on “data dredging” (ie, any analyses not planned at outset of study are clearly indicated or no retrospective unplanned analyses are reported); 18, the statistical tests used to assess the main outcomes are appropriate; 20, the main outcome measures used are accurate (valid and reliable) (either clearly described or referred to other studies); 27, the study had sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5% (sample sizes calculated to detect a difference of 5% and 5%).

Maximum value, 12.

### Characteristics of Included Studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Sample Size</th>
<th>Age, y*</th>
<th>Sex</th>
<th>OA Diagnosis of Severity</th>
<th>Symptomatic</th>
<th>Walking Surface</th>
<th>Gait Speed</th>
<th>Footwear</th>
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<th>Gait Data Adjusted for Height</th>
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<tr>
<td>Arminian et al</td>
<td>HOA, n = 11; control, n = 9</td>
<td>HOA, 60 ± 5; control, 63 ± 4</td>
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<td>Bejek et al</td>
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<td>Chiu et al</td>
<td>HOA, n = 20; control, n = 20</td>
<td>HOA, 57 ± 5; control, 60 ± 5</td>
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<td>Ennlåse et al</td>
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<td>HOA, 55 ± 5; control, 55 ± 1</td>
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<td>U (pre-THA)</td>
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<td>Tape measure and stopwatch</td>
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<td>Fang et al</td>
<td>HOA, n = 13; control, n = 13</td>
<td>HOA, 68 ± 6; control, 66 ± 5</td>
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<td>Foucher et al</td>
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<td>Hurwitz et al</td>
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<td>HOA, 63 ± 9; control, 62 ± 10</td>
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<td>MoCap</td>
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<td>Illyés and Kiss</td>
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<td>HOA, 66 ± 7; control, 61 ± 8</td>
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<td>Barefoot</td>
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<td>Illyés et al</td>
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<td>HOA, 72 ± 8; control, 61 ± 9</td>
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<td>Isobe et al</td>
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<td>HOA, 59 ± 9</td>
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<td>Kawano et al</td>
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<td>Kiss</td>
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<td>HOA, 70 ± 9; control, 69 ± 9</td>
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Table continues on page B3.
## TABLE 2

### Characteristics of Included Studies (continued)

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<th>Gait Data Adjusted for Height</th>
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<td>HOA, n = 39; control, n = 21</td>
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<td>HHS, symptomatic</td>
<td>Treadmill</td>
<td>Fixed</td>
<td>U</td>
<td>MoCap and instrumented treadmill</td>
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<td>HOA, n = 23; control, n = 10</td>
<td>HOA, 57 ± 5; control, U</td>
<td>HOA:17 male, 6 female; control:U</td>
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<td>HHS</td>
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<td>Barefoot</td>
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<td>MoCap</td>
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<td>HOA:30 female; control, 30 female</td>
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<td>Overground</td>
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<td>U</td>
<td>MoCap</td>
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<td>HOA, n = 11; control, n = 9</td>
<td>HOA, 61 ± 7; control, 60 ± 7</td>
<td>HOA:3 male, 8 female; control:2 male, 7 female</td>
<td>Moderate,Severe (X-ray)</td>
<td>Symptomatic</td>
<td>Overground</td>
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<td>Barefoot</td>
<td>MoCap</td>
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<td>HHS</td>
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<td>Self-selected, normal</td>
<td>Barefoot</td>
<td>MoCap</td>
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<td>HOA, 60 ± 9; control, 66 ± 6</td>
<td>HOA:15 male, 45 female; control:8 male, 22 female</td>
<td>X-ray (pre-THA)</td>
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<td>Self-selected, normal, slow, and fast</td>
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<td>HOA, n = 43; control, n = 26</td>
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<td>Vogt et alaf8</td>
<td>HOA, n = 12</td>
<td>HOA, 60.3 (44-74)</td>
<td>HOA:5 male, 7 female</td>
<td>U (pre-THA)</td>
<td>Symptomatic</td>
<td>Overground and treadmill</td>
<td>Self-selected, normal</td>
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<td>Tape measure and stopwatch and instrumented treadmill</td>
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<td>HOA, n = 30; control, n = 54</td>
<td>HOA, 31 (21-48); control, 29 (20-45)</td>
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<td>Overground</td>
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<td>Watskain et alaf9</td>
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<td>Early (X-ray)</td>
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<td>Overground</td>
<td>Self-selected, normal</td>
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<td>MoCap</td>
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*Abbreviations: HHS, symptomatic based on Harris hip scores; HOA, hip osteoarthritis; MoCap, motion capture; THA, total hip arthroplasty; U, unable to determine.

*Values are mean ± SD or mean ± SD (range).*
### A. Cadence at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA &lt; Control</th>
<th>Hip OA &gt; Control</th>
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<tr>
<td>Bejek et al</td>
<td>19</td>
<td>21</td>
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<td>Bejek et al</td>
<td>20</td>
<td>20</td>
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<tr>
<td>Illyés et al</td>
<td>20</td>
<td>21</td>
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<tr>
<td>Kiss</td>
<td>20</td>
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<td>Kiss and Illyés</td>
<td>39</td>
<td>21</td>
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<td>Kiss and Illyés</td>
<td>80</td>
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<tr>
<td>Pooled I² = 94%</td>
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</table>

Abbreviation: OA, osteoarthritis.

### B. Step Length (Affected Limb) at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA Affected &lt; Control</th>
<th>Hip OA Affected &gt; Control</th>
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<tbody>
<tr>
<td>Bejek et al</td>
<td>19</td>
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<td>Illyés et al</td>
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<td>Kiss and Illyés</td>
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<td>21</td>
<td></td>
<td></td>
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<tr>
<td>Kiss and Illyés</td>
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<tr>
<td>Pooled I² = 89%</td>
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Abbreviation: OA, osteoarthritis.

### C. Step Length (Contralateral Limb) at Fixed Walking Speeds

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<th>Hip OA Contralateral &gt; Control</th>
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<td>Kiss and Illyés</td>
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<tr>
<td>Kiss and Illyés</td>
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<td>40</td>
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<tr>
<td>Pooled I² = 90%</td>
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</table>

Abbreviation: OA, osteoarthritis.

**FIGURE 4.** Normalized effect sizes, 95% confidence intervals, and sample sizes for studies comparing (A) cadence, (B) step length of affected limb, and (C) step length of contralateral limb at treadmill-fixed walking speeds between individuals with hip osteoarthritis and control participants. The pooled effect size and its 95% confidence interval and the homogeneity statistic (I²) were calculated using a fixed-effects model, where individual study results were weighted by the inverse of their variance. For those studies that reported spatial-temporal gait data across multiple conditions, study-wise pooled effect sizes and 95% confidence intervals, weighted by the inverse of the variance of condition-wise effect sizes, were calculated and used in the calculation of pooled effect sizes and homogeneity statistics.
### ONLINE FIGURES

#### A. Swing Duration (Affected Limb) at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA Affected &lt; Control</th>
<th>Hip OA Affected &gt; Control</th>
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<tbody>
<tr>
<td>Bejek et al.</td>
<td>19</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bejek et al.</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illyés et al.</td>
<td>20</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés</td>
<td>39</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés</td>
<td>80</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pooled I² = 10%</td>
<td>198</td>
<td>143</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviation: OA, osteoarthritis.

#### B. Swing Duration (Contralateral Limb) at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA Contralateral &lt; Control</th>
<th>Hip OA Contralateral &gt; Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bejek et al.</td>
<td>19</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bejek et al.</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Illyés et al.</td>
<td>20</td>
<td>21</td>
<td></td>
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</tr>
<tr>
<td>Kiss</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés</td>
<td>39</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés</td>
<td>80</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pooled I² = 65%</td>
<td>198</td>
<td>143</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviation: OA, osteoarthritis.

**FIGURE 7.** Normalized effect sizes, 95% confidence intervals, and sample sizes for studies comparing (A) swing duration of affected limb and (B) swing duration of contralateral limb at treadmill-fixed walking speeds between individuals with hip osteoarthritis and control participants. The pooled effect size and its 95% confidence interval and the homogeneity statistic ($I^2$) were calculated using a fixed-effects model, where individual study results were weighted by the inverse of their variance. For those studies that reported spatial-temporal gait data across multiple conditions, study-wise pooled effect sizes and 95% confidence intervals, weighted by the inverse of the variance of condition-wise effect sizes, were calculated and used in the calculation of pooled effect sizes and homogeneity statistics.
A. Double-Support Duration (Affected Limb) at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA &lt; Control</th>
<th>Hip OA &gt; Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bejek et al\cite{6}</td>
<td>19</td>
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<td>Bejek et al\cite{7}</td>
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</tr>
<tr>
<td>Illyés et al\cite{8}</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Kiss\cite{10}</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés\cite{12}</td>
<td>39</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés\cite{13}</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pooled I² = 55%</td>
<td>198</td>
<td>143</td>
<td></td>
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</tr>
</tbody>
</table>

Abbreviation: OA, osteoarthritis.

B. Step Width (Affected Limb) at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA Affected &lt; Control</th>
<th>Hip OA Affected &gt; Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bejek et al\cite{6}</td>
<td>19</td>
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<td></td>
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<tr>
<td>Bejek et al\cite{7}</td>
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<td>20</td>
<td></td>
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</tr>
<tr>
<td>Illyés et al\cite{8}</td>
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<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés\cite{12}</td>
<td>39</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés\cite{13}</td>
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<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pooled I² = 95%</td>
<td>178</td>
<td>123</td>
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<td></td>
</tr>
</tbody>
</table>

Abbreviation: OA, osteoarthritis.

C. Step Width (Contralateral Limb) at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Hip OA, n</th>
<th>Control, n</th>
<th>Hip OA Contralateral &lt; Control</th>
<th>Hip OA Contralateral &gt; Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bejek et al\cite{6}</td>
<td>19</td>
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<td></td>
</tr>
<tr>
<td>Illyés et al\cite{8}</td>
<td>20</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés\cite{12}</td>
<td>39</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés\cite{13}</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pooled I² = 86%</td>
<td>118</td>
<td>103</td>
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</tbody>
</table>

Abbreviation: OA, osteoarthritis.

**FIGURE 8.** Normalized effect sizes, 95% confidence intervals, and sample sizes for studies comparing (A) double-support duration, (B) step width of affected limb, and (C) step width of contralateral limb at treadmill-fixed walking speeds between individuals with hip osteoarthritis and controls. The pooled effect size and its 95% confidence interval and the homogeneity statistic (I²) were calculated using a fixed-effects model, where individual study results were weighted by the inverse of their variance. For those studies that reported spatial-temporal gait data across multiple conditions, study-wise pooled effect sizes and 95% confidence intervals, weighted by the inverse of the variance of condition-wise effect sizes, were calculated and used in the calculation of pooled effect sizes and homogeneity statistics.
### A. Step Length at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Affected Limb, n</th>
<th>Contralateral Limb, n</th>
<th>Affected Limb &lt; Contralateral Limb</th>
<th>Affected Limb &gt; Contralateral Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bejek et al.⁶</td>
<td>19</td>
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<td>Bejek et al.¹</td>
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<tr>
<td>Illyés et al.³⁷</td>
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<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss⁶²</td>
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<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés⁴⁴</td>
<td>39</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés⁴⁴</td>
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<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pooled F = 0%</td>
<td>198</td>
<td>198</td>
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</tr>
</tbody>
</table>

Abbreviation: OA, osteoarthritis.

### B. Swing Duration at Fixed Walking Speeds

<table>
<thead>
<tr>
<th>Study</th>
<th>Affected Limb, n</th>
<th>Contralateral Limb, n</th>
<th>Affected Limb &lt; Contralateral Limb</th>
<th>Affected Limb &gt; Contralateral Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bejek et al.⁶</td>
<td>19</td>
<td>19</td>
<td></td>
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</tr>
<tr>
<td>Bejek et al.¹</td>
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<td></td>
</tr>
<tr>
<td>Illyés et al.³⁷</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss⁶²</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés⁴⁴</td>
<td>39</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiss and Illyés⁴⁴</td>
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<tr>
<td>Pooled F = 80%</td>
<td>198</td>
<td>198</td>
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</tr>
</tbody>
</table>

Abbreviation: OA, osteoarthritis.

**FIGURE 10.** Normalized effect sizes, 95% confidence intervals, and sample sizes for studies comparing (A) step length and (B) swing duration at treadmill-fixed walking speeds between affected and contralateral limbs of individuals with hip osteoarthritis. The pooled effect size and its 95% confidence interval and the homogeneity statistic (I²) were calculated using a fixed-effects model, where individual study results were weighted by the inverse of their variance. For those studies that reported spatial-temporal gait data across multiple conditions, study-wise pooled effect sizes and 95% confidence intervals, weighted by the inverse of the variance of condition-wise effect sizes, were calculated and used in the calculation of pooled effect sizes and homogeneity statistics.