# Does the intensity of daily walking matter for protecting against the development of a slow gait speed in people with or at high risk of Knee Osteoarthritis?

Fenton, Sally; Neogi, Tuhina; Dunlop, Dorothy; Nevitt, Michael; Doherty, Michael; Duda, Joan L; Klocke, Rainer; Abhishek, Abhishek; Rushton, Alison; Zhang, Weiya; Lewis, Cora E.; Torner, James; Kitas, George; White, Daniel K.; Multicenter Osteoarthritis Group

*DOI:*
10.1016/j.joca.2018.04.015

## INTRODUCTION

Knee osteoarthritis (OA) is a risk factor for a rapid decline in walking or gait speed in middle to older aged adults,[1] and functional limitation in general.[2] Since a slow gait speed is well recognized as a risk factor for mortality[3] and persistent functional limitation in older adults,[4] it is important to prevent reductions in gait speed in people with knee OA.

Physical activity is recommended to prevent slow gait and functional limitation in OA.[5-7] In particular, daily walking, i.e., taking more steps/day, is underlined as is the single most crucial movement behaviour to encourage,[8] as it is the most common type of physical activity that older adults employ for exercise.[9-12] Evidence suggests that walking >6000 steps/day can serve to preserve gait speed in knee OA.[13] However, it is not known whether the *intensity* of steps accumulated is also relevant for preventing a slow gait speed in this population. For instance, walking can be purposeful and of a moderate-to-vigorous intensity (e.g., brisk walking, or walking to load/unload a car), or it can be of a lighter intensity, e.g., taking a stroll in a park.[8,14]

Since the total hours available in one day to participate in physical activity are finite (i.e., limited to 24 hours) participating in one activity comes at the cost of not engaging in another. For the present study, we are most interested in understanding the effects of replacing not walking for walking at different intensities on incident slow gait speed. Analytically, Isotemporal substitution offers a novel technique to statistically estimate the value of displacing one behaviour with an alternative activity. This is an advance over traditional methods to quantify the association between an exposure and outcome (such as regression models), in which only the effect of "adding", rather than substituting an activity type can be examined.[15,16] In particular, isotemporal substitution will enable investigation of the 'time-substitution effects' of replacing an identical time period of not walking, with walking at light or moderate-to-vigorous intensities on incident slow gait speed – i.e., the ability to walk >1.0 meters/second (m/s) and >1.2 m/s. These thresholds are considered to discriminate those with and without risk of mortality and loss of independent and autonomous functioning within their community, respectively.

The purpose of this study was therefore to investigate the association of substituting time spent not walking with walking at very-light (i.e., 1–49 steps/minute), light (50–100 steps/min), and moderate-to-vigorous walking (>100 steps/min) intensities for incident slow gait speed over a two year period in people with, or at high risk of, knee OA.

## METHODS

### Study sample

We used data from two longitudinal cohort studies, specifically the Multicenter Osteoarthritis (MOST) study and the Osteoarthritis Initiative (OAI). In both studies, participants were community dwelling adults who have, or who are at high risk of developing knee OA at baseline. Increased risk was identified from age-specific criteria for established risk factors including knee symptoms in the past 12 months,[17] being overweight from gender-specific cut-points,[17] knee injury causing difficulty walking for at least one week,[17,18] any knee surgery history,[19] family history of a total knee replacement,[20] Heberden's nodes,[17,21] or repetitive knee bending at work or outside of work.[22] Detailed descriptions of MOST study and OAI eligibility criteria have been published elsewhere.[23,24] Briefly, the MOST study enrolled people aged 50 to 79 years, from communities in and surrounding Birmingham, Alabama, and Iowa City. The OAI recruited people aged 45 to 79 years from four clinical sites (Baltimore, Maryland; Pittsburgh, Pennsylvania; Pawtucket, Rhode Island; and Columbus Ohio). Study protocols were approved by the relevant institutional review boards. All participants provided informed consent to participate.

This study focused on sub-samples of the MOST and OAI cohorts who consented to undertake objective assessment of physical activity (via activity monitors). This occurred for the first time at the 60-month (MOST) and 48-month (OAI) study visits. We also used data collected two years later at the 84-month (MOST) and 72-month (OAI) study visits (Figure

1), in order to determine incidence of slow gait speed. For MOST, objective activity monitor data were collected from 2330 individuals between May 2009 and January 2011. For OAI, a total of 2125 participants provided objective activity monitor data between August 2008 and July 2010. For the purpose of this study, 60- and 48-month study visits are considered 'baseline' and 84- and 72-months the two-year follow up for MOST and OAI participants, respectively.

**Measures**

**Study exposure**

*Intensity of daily walking*

Daily walking was measured using an accelerometer-enabled physical activity monitor in both cohorts. For the MOST study, walking intensity was assessed using the StepWatch™ activity monitor - a small (70 x 50 x 20mm), waterproof device that is worn around the ankle and records the number of strides taken each minute. To calculate the number of steps, the stride output is doubled. In the OAI study, daily walking was measured via the GT1M Actigraph - a small uniaxial accelerometer that was worn on the right hip and measures acceleration and deceleration along a vertical axis. Both the Stepwatch™ and GT1M Actigraph have been validated for step count against several reference standard measures of step frequency, including in samples of older adults.[25-27] Participants were provided with written and verbal instructions regarding monitor wear, removal and replacement. In both studies, participants were asked to wear the device during waking hours for 7 consecutive days. They were requested to remove the monitor only for water-based activities (e.g., swimming, showering), or sleeping.

Non-wear time was determined by identifying sustained periods of little or zero activity from data recorded by activity monitors. Non-wear criteria was applied in accordance with previous published studies validating non-wear criteria specifically for the StepWatch[36] and Actigraph.[37] Specifically, in the MOST cohort, we defined non-wear as ≥180 minutes of consecutive 0 steps.[28,29] For the OAI sample, non-wear was identified where the monitor had registered ≥ 90 minutes of consecutive activity counts <100.[29] In both cohorts, we defined a valid day as ≥10 hours valid wear time.[29]

Walking intensity was classified according to step cadence recorded by the physical activity monitors. Specifically, <1 step/min was defined as not walking, 1 - 49 steps/min as very-light intensity walking, 50 - 100 steps/min as light intensity walking, and >100 steps/min as moderate-to-vigorous intensity walking.[8,30-32] We split light intensity walking into two categories (very-light and light), as behaviours undertaken between 1 and 100 steps/min are likely to comprise a wide range of behaviours (e.g., standing with incidental movement, household chores, walking at <4km/hour). As such, it is possible that time spent walking at the lower vs. upper end of the 'light intensity' spectrum may hold different effects for health for people with knee OA.[15]

**Study outcomes**

*Slow Gait Speed*

Gait speed was measured in both MOST and OAI studies in m/s on the basis of average speed over two 20-meter timed walk tests [i.e., 20 metres ÷ test time (seconds)].[13,33] The test was conducted in an unobstructed corridor and timing started when the first foot crossed the start line, and ended after the last foot crossed the finish line. Gait speed has been shown to have high test-re-test reliability in people with knee OA.[33]

We defined two study outcomes from the 20-metre walk:

1) *Gait speed <1.0 m/s:* Walking < 1.0 m/s is associated with mortality and limitations in physical functioning among community dwelling older adults.[3,34]
2) *Gait speed <1.2 m/s:* Walking > 1.2 m/s is a minimum speed necessary to cross streets using timed signals.[35] Thus, walking at a speed at or above 1.2 m/s is a reasonable proxy for the ability to navigate independently in the community,[36] and a speed <1.2 m/s may represent difficulty walking in the community. Several studies in the USA, Canada, and

Europe have recently employed this threshold to represent a community walking speed.[37,38]

*Data reduction*

Participants who provided > 4 days of valid activity monitor data at baseline were included in present analyses (MOST, N = 1731, OAI, N = 1925).[39,40] Analyses were further restricted to those without slow gait speed at baseline. For < 1.0 m/s outcome, a total of 1342 and 1551 participants in MOST and OAI respectively, were included in the analytic data set. For < 1.2 m/s outcome, a total of 878 and 1221, were included for MOST and OAI respectively. **Figure 1.**

**Potential confounders**

Study covariates were included on the basis of previously associations with physical activity and gait speed,[41,42] and covariate values collected at our study baseline were included in analyses (MOST 60-month, OAI 48-month) (OAI) study visit as follows; age; sex; body-mass-index (BMI); study site; ethnicity (White, African American, other); educational attainment (< some college vs. ≥ college); marital status (married, single, divorced, separated); self-reported comorbidities (Charlson comorbidity index, ≥1 vs. none); symptoms of depression symptoms (Centre for Epidemiologic Studies Depression Scale, ≥16 vs. <16); and knee pain on a visual analogue scale (MOST for past 30 days 0 – 100; OAI for past 7 days 0-10). All variables were assessed via direct measurement, interview and/or questionnaire. Instruments and data collection procedures have been previously described in detail elsewhere.[23,24]

**Statistical analyses**

All analyses were conducted separately for MOST and OAI study samples due to differences in study methodologies in regards to exposure variables (i.e., walking intensity measured via the StepWatch™ vs. Actigraph). First, descriptive statistics were computed. Next, regressions were employed to calculate Relative Risk Ratios (RR) using regression models with a log-link function and robust standard errors. In particular, we employed isotemporal substitution within regression models to evaluate the effect (i.e., relative risk reduction) of replacing not walking, with equal periods of very-light, light and moderate-to-vigorous intensity walking, on study outcomes.[15,16] This analytical approach enables investigation of increasing engagement in different intensities of walking and simultaneously decreasing time spent not walking on the relative risk of developing slow gait speed two years later. In this way, are able to examine the *combined* effects of displacing minutes of not walking, with equal minutes of walking at specific intensities. This is in contrast to simple regression models, in which only the effect of "adding", rather than substituting an activity type can be examined.[15] That is, only the independent effects of increasing one behaviour can be investigated, whilst controlling for a constant (and therefore unchanging) level of another.

We utilised isotemporal models by including a variable for; 1) the total time (i.e., the sum of time spent; not walking + very-light + light + moderate-to-vigorous walking) and 2) four separate variables to represent each unique walking-intensity to the model simultaneously (i.e., one each for; not walking, very-light, light, and moderate-to-vigorous walking). The unique activity variable representing time spent *not walking* was dropped from the model to estimate the effects of replacing not walking, with walking at different intensities.[16]

Before entry into models, all four walking intensity categories were divided by a constant to represent the 'duration of substitution', in order to improve the clinical implications of study findings. For example, to estimate the effects of replacing 5 minutes of not walking, with 5 minutes of walking at different intensities on study outcomes, all variables were divided by 5 to represent an increase of 5 minutes/day within each walking intensity category. We repeated analysis dividing walking categories by 10 and 20 to represent an increase of walking 10 and 20 minutes/day, respectively. All models were adjusted for potential confounders.

## RESULTS

Of the 1731 participants included in the MOST analytic dataset, the mean (SD) age was 67.2 (7.7) years and 59.8% were women. Of the 1925 participants included in the OAI analytic dataset, the mean (SD) age was 65.1 (9.1) years and 55.2% were women. **Table 1.** Participants not included in the analytic data set, (i.e. those who had baseline but not follow-up data), were in general more likely to be non-white, have pain in the lower body, have less than a college education, have comorbid conditions, and have higher BMI and higher knee pain intensity at baseline compared with those included in the analytic dataset. **Supplemental Table 1.**

In general, those who did not develop slow gait speed spent more time walking at very-light, light and moderate-to-vigorous intensities at baseline compared with those who developed slow gait speed at 2 years. **Table 2.**

*Gait speed <1.0 m/s*

The cumulative incidence of a gait speed < 1.0 m/s over two years was 8.8% (n = 108/1342) and 4.5% (n = 70/1551) in the MOST and OAI cohorts, respectively. Replacing not walking with 5 to 20 min/day of moderate-to-vigorous walking reduced the risk by 13% to 49% in MOST and 33% to 79% in OAI, which both met statistical significance. **Figure 2.** Replacement with walking 5 to 20 min/day at a light intensity had a 5% to 20% reduction in risk in MOST and 10% to 34% reduction in risk in OAI, and these effects did not meet statistical significance. Replacing time not walking with very-light intensity walking did not materially change the risk of developing a gait speed < 1.0 m/s in both cohorts. For unadjusted effect estimates, see **Supplemental Table 2.**

*Gait speed <1.2 m/s*

The development of a gait speed < 1.2 m/s over two years was 17.8% (n = 156/878) of the MOST study sample, and 13.3% (n = 163/1221) of OAI participants. Replacement with 5 to 20 min/day of moderate-to-vigorous walking demonstrated risk reductions between 8% to

27% in MOST and 10% to 35% in OAI. However, effects did not meet statistical significance. **Figure 3.** Similarly, replacing not walking, with 5 to 20 min/day of walking at a light intensity or very-light intensity revealed small risk reductions in both cohorts (light = 1-4% in MOST, 2-10% in OAI; very-light = 1-2% in MOST, 1-4% in OAI), which were not statistically significant. For unadjusted effect estimates, see **Supplemental Table 2.**

## DISCUSSION

We investigated the association of substituting time spent not walking with walking at different intensities for protecting against the development of slow gait speeds two years later, in people with or at high risk of knee OA. We found that replacing not walking with equal periods of walking at a moderate-to-vigorous intensity (>100 steps/min) had a small to moderate effect on reducing the risk of developing a slow gait speed <1.0 m/s two years later. However, we found attenuated effects for light intensity walking (50 - 100 steps/min) that did not meet statistical significance, and observed no effect of very-light intensity walking (1 - 49 steps/min).

Past work employing isotemporal substitution analyses has demonstrated the significance of light-intensity physical activity for prevention of poor physical health and reduced risk of mortality among older adults.[15,43] Such findings have contributed towards the evidence base underpinning recommendations for the promotion of light physical activity among populations for whom regular engagement in higher intensity physical activity may present a challenge (including knee OA).[44] Arguably our results, which demonstrate that for people with, or at high risk of knee OA, light-intensity walking may not produce the same functional gains as moderate-to-vigorous walking, are particularly important.

Our findings suggest that walking at a moderate-to-vigorous intensity may be necessary to prevent the development of a slow gait speed <1.0 m/s. This is an important finding given that this critically slow gait speed is a known risk factor for death,[3] persistent lower extremity limitation, and hospitalization in older adults.[4] Thus, preventing the development of slow gait, from taking more moderate-to-vigorous steps/day is noteworthy for people with knee OA, who are already at high risk of developing functional limitation.

These findings extend previous work regarding recommendations for daily step accumulation in knee OA (i.e., >6000 steps/day),[13] by adding the caveat that steps may need to be at a moderate intensity in order to significantly protect against critically slow gait speed. One way to increase such steps is to use a joint step and time goal. Indeed, there is expert consensus to indicate that setting step cadence goals - in addition to step frequency goals - might help individuals engage in more moderate-to-vigorous physical activity.[8] For example, a previous study investigating messaging of physical activity goals for Latina women found a goal of 3000 steps in 30 minutes had the best increase in time spent in moderate-to-vigorous physical activity, compared to a step goal of walking 10,000 steps/day or a self-selected step goal.[45] Considering the emerging widespread use of commercially available fitness trackers to record steps among the general population, we believe our findings are particularly timely.

One reason why moderate-to-vigorous walking, relative to lighter intensity walking may be protective against slow gait, is because of the significant physiological response required by the lower-body musculature to generate faster more frequent walking. It is well evidenced that moderate-to-vigorous physical activity is associated with increased muscular strength,[46-48] and that higher lower-extremity muscular strength reduces the risk of functional decline among at risk cohorts.[49,50] Our findings are consistent with the Australian Diabetes, Obesity and Lifestyle Study, which found steps accumulated at a moderate-to-vigorous intensity were more consistently, and strongly linked to lower-extremity muscular strength than steps taken at a light intensity.[47]

Still, it is noteworthy that whilst our analyses revealed only small associations for light-intensity walking that did not meet statistical significance, the size of the risk reductions were comparable for replacement of not walking with 20 minutes of light-intensity walking vs. 5 minutes of moderate-to-vigorous intensity walking (i.e., 20% vs 13% (MOST), and 34% vs 33% (OAI), respectively). This is perhaps because these replacement durations are more comparable at the relative level (i.e., typically between a 40-100% increase). Thus, it is possible that trading not walking with light-intensity walking of longer durations, may offer an intermediate step to promoting engagement in moderate-to-vigorous intensity walking. Indeed, the avoidance of time spent in no or very-light activity for short time periods each day, may be a first realistic goal for people with knee pain and co-existing mobility issues.

Strengths of this study include parallel analyses of longitudinal data from two large-scale cohort studies – MOST and OAI and the objective assessment of daily walking in both cohorts. There are a number of limitations to the present study. First, isotemporal regression models permit investigation of only theoretical relationships, and do not represent observed changes in physical activity. In addition, as the confidence intervals for all effect sizes are wide, the reported associations between walking intensity and risk of developing slow gait speed may be much smaller (or larger) than suggested by the point estimates. Results should therefore be interpreted with some caution. Second, there is a potential for reverse-causation, i.e., individuals who walk faster are able to achieve moderate intensity with less effort than those who walk slower. We mitigate this by only including study participants who are without slow gait speed at our study baseline. However, it is still possible classification bias at baseline in regards to baseline gait speeds may have influenced study findings – i.e., participants with a gait speed just above the critical thresholds (1.0 and 1.2 m/s) may be at a greater risk of falling below the threshold after two years, than participants with a much higher baseline gait speed. Thus, to definitively test the effect of replacing variable time periods of not walking, with walking at different intensities on gait speed, a controlled clinical trial is required. Such a trial may be impractical, however, given the low incidence of our study outcomes, <20%, and the associated cost of a RCT. Third, it is not known if walking at a moderate-to-vigorous intensity was accumulated in bouts e.g., continuous walking episodes, or across interrupted minutes of walking. Finally, we only evaluated our study outcome over two years. It is likely a higher incidence may occur with a longer follow-up period. Nevertheless, these findings may provide support that walking at a moderate-to-vigorous intensity (for longer durations) is associated with maintenance of gait speed above critical levels in people with, or at high risk of knee OA. Indeed, where moderate-to-vigorous walking can be encouraged or maintained from knee OA onset, our findings highlight the positive consequences of a cyclic relationship between walking intensity and gait speed.

**Conclusions**

We found that increasing time in moderate-to-vigorous walking may prevent slow gait speed in people with or at high risk of knee OA. These findings may support the importance of recommending a moderate-to-vigorous walking intensity in addition to a step goal, in order reduce the risk of developing critical slow gait speeds in this population. These recommendations need to be confirmed in controlled clinical trials.

**Author contributions**

SF (s.a.m.fenton@bham.ac.uk) and DW (dkw@udel.edu) had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. SF, JLD, AR, AA, RK and DW: *study concept and analytical design*. SF, TN and DW: *analysis and interpretation of data*. SF and DW: *drafting of the manuscript*. SF, TN, DD, MN, MD, JD, RK, AA, AR, WZ, CEL, JT, GK and DW: *critical revision of the manuscript for important intellectual content*. SF and DW: *statistical analysis*. SF, TN, DD, MN, MD, JD, RK, AA, AR, WZ, CEL, JT, GK and DW: *final approval for the version to be published.*

**Role of the funding source:** The Multi-center Osteoarthritis Study (MOST) and Osteoarthritis Initiative (OAI) were funded by the National Institutes of Health [MOST grants; AG19069 (MN), AG18820 (DF), AG18947 (CL), AG18832 (JT), NIAMS K24AR070892 (TN), U54-GM104941, NIH K12 HD055931, NIH R21AR071079 (DW); OAI grants; R01 AR055287 (DD). The funders of this manuscript did not have any role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; and preparation, review, or approval of the manuscript.

**Conflict of interest**

All authors declare no conflicts of interest.

## References

1. White DK, Niu J, Zhang Y. Is symptomatic knee osteoarthritis a risk factor for a trajectory of fast decline in gait speed? Results from a longitudinal cohort study. *Arthritis Care and Research (Hoboken).* 2013;65(2):187-194.
2. Guccione AA, Felson DT, Anderson JJ, Anthony JM, Zhang Y, Wilson PW, et al. The effects of specific medical conditions on the functional limitations of elders in the Framingham Study. *American Journal of Public Health.* 1994;84(3):351-358.
3. Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, et al. Gait speed and survival in older adults. *Journal of the American Medical Association.* 2011;305(1):50-58.
4. Cesari M, Kritchevsky SB, Penninx BW, Nicklas BJ, Simonsick EM, Newman AB, et al. Prognostic value of usual gait speed in well-functioning older people--results from the Health, Aging and Body Composition Study. *Journal of the American Geriatrics Society.* 2005;53(10):1675-1680.
5. Tanaka R, Ozawa J, Kito N, Moriyama H. Effects of exercise therapy on walking ability in individuals with knee osteoarthritis: a systematic review and meta-analysis of randomised controlled trials. *Clinical Rehabilitation.* 2016;30(1):36-52.
6. Golightly YM, Allen KD, Caine DJ. A Comprehensive Review of the Effectiveness of Different Exercise Programs for Patients with Osteoarthritis. *The Physician and Sports Medicine.* 2012;40(4):52-65.
7. Zoeller RF. Physical Activity: Physical Activity in the Management of Osteoarthritis of the Knee and Hip. *American Journal of Lifestyle Medicine.* 2007;1(4):264-266.
8. Tudor-Locke C, Rowe DA. Using Cadence to Study Free-Living Ambulatory Behaviour. *Sports Medicine.* 2012;42(5):381-398.
9. Nelson ME, Rejeski WJ, Blair SN, Duncan PW, Judge JO, King AC, et al. Physical Activity and Public Health in Older Adults: Recommendation from the American College of Sports Medicine and the American Heart Association. *Medicine and Science in Sports and Exercise.* 2007;39(8):1435-1445.
10. King AC, Rejeski WJ, Buchner DM. Physical activity interventions targeting older adultsa: A critical review and recommendations. *American Journal of Preventive Medicine.* 1998;15(4):316-333.
11. LIFE Study Investigators, Pahor M, Blair SN, Espeland M, Fielding R, Gill TM, et al. Effects of a Physical Activity Intervention on Measures of Physical Performance: Results of the Lifestyle Interventions and Independence for Elders Pilot (LIFE-P) Study. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences.* 2006;61(11):1157-1165.

12. *Physical Activity and Health: A Report of the Surgeon General.* Office of the Surgeon General, National Center for Chronic Disease Prevention, Health Promotion, Presidents Council on Physical Fitness, Sports (USA).1996.

13. White DK, Tudor-Locke C, Zhang Y, Fielding R, LaValley M, Felson DT, et al. Daily walking and the risk of incident functional limitation in knee OA: An observational study. *Arthritis Care & Research (Hoboken).* 2014;66(9):1328-1336.

14. Ainsworth BE, Haskell WL, Whitt MC, Irwin ML, Swartz AM, Strath SJ, et al. Compendium of Physical Activities: an update of activity codes and MET intensities. *Medicine and Science in Sports and Exercise.* 2000;32(9):S498-S516.

15. Buman MP, Hekler EB, Haskell WL, Pruitt L, Conway TL, Cain KL, et al. Objective light-intensity physical activity associations with rated health in older adults. *American Jouranl of Epidemiology.* 2010;172(10):1155-1165.

16. Mekary RA, Willett WC, Hu FB, Ding EL. Isotemporal Substitution Paradigm for Physical Activity Epidemiology and Weight Change. *American Journal of Epidemiology.* 2009;170(4):519-527.

17. Cooper C, Snow S, McAlindon TE, Kellingray S, Stuart B, Coggon D, et al. Risk factors for the incidence and progression of radiographic knee osteoarthritis. *Arthritis and Rheumatism.* 2000;43(5):995-1000.

18. Felson DT, Zhang Y, Hannan MT, Naimark A, Weissman B, Aliabadi P, et al. Risk factors for incident radiographic knee osteoarthritis in the elderly: the Framingham Study. *Arthritis and Rheumatism.* 1997;40(4):728-733.

19. Roos H, Lauren M, Adalberth T, Roos EM, Jonsson K, Lohmander LS. Knee osteoarthritis after meniscectomy: prevalence of radiographic changes after twenty-one years, compared with matched controls. *Arthritis and Rheumatism.* 1998;41(4):687-693.

20. Chitnavis J, Sinsheimer JS, Clipsham K, Loughlin J, Sykes B, Burge PD, et al. Genetic influences in end-stage osteoarthritis. Sibling risks of hip and knee replacement for idiopathic osteoarthritis. *Journal of Bone Joint Surgery. British Volume.* 1997;79(4):660-664.

21. Hart DJ, Doyle DV, Spector TD. Incidence and risk factors for radiographic knee osteoarthritis in middle-aged women: the Chingford Study. *Arthritis and Rheumtism.* 1999;42(1):17-24.

22. Felson DT, Hannan MT, Naimark A, Berkeley J, Gordon G, Wilson PW, et al. Occupational physical demands, knee bending, and knee osteoarthritis: results from the Framingham Study. *Journal of Rheumatology.* 1991;18(10):1587-1592.

23. Felson DT, Niu J, Yang T, Torner J, Lewis CE, Aliabadi P, et al. Physical activity, alignment and knee osteoarthritis: Data from MOST and the OAI. *Osteoarthritis and Cartilage.* 2013;21(6):789-795.

24. The Osteoarthritis Initiative: a multi-center observational study of men and women. 2016. Accessed 27/09/2016.

25. Resnick B, Nahm E-S, Orwig D, Zimmerman SS, Magaziner J. Measurement of Activity in Older Adults: Reliability and Validity of the Step Activity Monitor. *Journal of Nursing Measurement.* 2001;9(3):275-290.

26. Karabulut M, Crouter SE, Bassett DR. Comparison of two waist-mounted and two ankle-mounted electronic pedometers. *European Journal of Applied Physiology.* 2005;95(4):335-343.

27. Brage S, Wedderkopp N, Franks PW, Bo Andersen L, Froberg K. Reexamination of Validity and Reliability of the CSA Monitor in Walking and Running. *Medicine and Science in Sports and Exercise.* 2003;35(8):1447-1454.

28. King WC, Li J, Leishear K, Mitchell JE, Belle SH. Determining activity monitor wear time: an influential decision rule. *Journal of Physical Activity and Health.* 2011;8(4):566-580.

29. Song J, Semanik P, Sharma L, Chang RW, Hochberg MC, Mysiw WJ, et al. Assessing Physical Activity in Persons with Knee Osteoarthritis Using Accelerometers: Data in the Osteoarthritis Initiative. *Arthritis Care and Research (Hoboken).* 2010;62(12):1724-1732.

30. Marshall SJ, Levy SS, Tudor-Locke CE, Kolkhorst FW, Wooten KM, Ji M, et al. Translating Physical Activity Recommendations into a Pedometer-Based Step Goal: 3000 Steps in 30 Minutes. *American Journal of Preventive Medicine.* 2009;36(5):410-415.

31. Abel M, Hannon J, Mullineaux D, Beighle A. Determination of Step Rate Thresholds Corresponding to Physical Activity Intensity Classifications in Adults. *Journal of Physical Activity and Health.* 2011;8(1):45-51.

32. Tudor-Locke C, Camhi SM, Leonardi C, Johnson WD, Katzmarzyk PT, Earnest CP, et al. Patterns of adult stepping cadence in the 2005–2006 NHANES. *Preventive Medicine.* 2011;53(3):178-181.

33. Motyl JM, Driban JB, McAdams E, Price LL, McAlindon TE. Test-retest reliability and sensitivity of the 20-meter walk test among patients with knee osteoarthritis. *BMC Musculoskeletal Disorders.* 2013;14:166-166.

34. Abellan Van Kan G, Rolland Y, Andrieu S, Bauer J, Beauchet O, Bonnefoy M, et al. Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling

older people an International Academy on Nutrition and Aging (IANA) Task Force. *The Journal of Nutrition, Health and Aging.* 2009;13(10):881-889.

35. Langlois JA, Keyl PM, Guralnik JM, Foley DJ, Marottoli RA, Wallace RB. Characteristics of older pedestrians who have difficulty crossing the street. *American Journal of Public Health.* 1997;87(3):393-397.

36. Andrews AW, Chinworth SA, Bourassa M, Garvin M, Benton D, Tanner S. Update on distance and velocity requirements for community ambulation. *Journal of Geriatric Physical Therapy.* 2010;33(3):128-134.

37. Asher L, Aresu M, Falaschetti E, Mindell J. Most older pedestrians are unable to cross the road in time: a cross-sectional study. *Age and Ageing.* 2012;41(5):690-694.

38. Brown KC, Hanson HM, Firmani F, Liu D, McAllister MM, Merali K, et al. Gait Speed and Variability for Usual Pace and Pedestrian Crossing Conditions in Older Adults Using the GAITRite Walkway. *Gerontology and Geriatric Medicine.* 2015;1:2333721415618858.

39. Mudge S, Taylor D, Chang O, Wong R. Test-Retest Reliability of the StepWatch Activity Monitor Outputs in Healthy Adults. *Journal of Physical Activity and Health.* 2010;7(5):671-676.

40. Welk GJ, Schaben JA, Morrow JRJ. Reliability of Accelerometry-Based Activity Monitors: A Generalizability Study. *Medicine and Science in Sports and Exercise.* 2004;36(9):1637-1645.

41. Kang M, Marshall SJ, Barreira T, Lee J. Effect of pedometer-based physical activity interventions: a meta-analysis. *Research Quarterly for Exercise and Sport.* 2009;80(3):648-655.

42. Sharma L, Cahue S, Song J, Hayes K, Pai Y-C, Dunlop D. Physical functioning over three years in knee osteoarthritis: Role of psychosocial, local mechanical, and neuromuscular factors. *Arthritis and Rheumatism.* 2003;48(12):3359-3370.

43. Schmid D, Ricci C, Baumeister SE, Leitzmann MF. Replacing Sedentary Time with Physical Activity in Relation to Mortality. *Medicine and Science in Sports and Exercise.* 2016;48(7):1312-1319.

44. Manns PJ, Dunstan DW, Owen N, Healy GN. Addressing the nonexercise part of the activity continuum: a more realistic and achievable approach to activity programming for adults with mobility disability? *Physical Therapy.* 2012;92(4):614-625.

45. Marshall SJ, Nicaise V, Ji M, Huerta C, Haubenstricker J, Levy SS, et al. Using step cadence goals to increase moderate-to-vigorous-intensity physical activity. *Medicine and Science in Sports and Exercise.* 2013;45(3):592-602.

46. Foong YC, Chherawala N, Aitken D, Scott D, Winzenberg T, Jones G. Accelerometer-determined physical activity, muscle mass, and leg strength in

community-dwelling older adults. *Journal of Cachexia, Sarcopenia and Muscle.* 2016;7(3):275-283.

47. Reid N, Daly RM, Winkler EA, Gardiner PA, Eakin EG, Owen N, et al. Associations of Monitor-Assessed Activity with Performance-Based Physical Function. *PLoS One.* 2016;11(4):e0153398.

48. Wu F, Wills K, Laslett LL, Oldenburg B, Jones G, Winzenberg T. Moderate-to-Vigorous Physical Activity But Not Sedentary Time Is Associated With Musculoskeletal Health Outcomes in a Cohort of Australian Middle-Aged Women. *Journal of Bone and Mineral Research.* 2017;32(4):708-715.

49. Reid KF, Naumova EN, Carabello RJ, Phillips EM, Fielding RA. Lower extremity muscle mass predicts functional performance in mobility-limited elders. *Journal of Nutrition, Health and Aging.* 2008;12(7):493-498.

50. Schaap LA, Koster A, Visser M. Adiposity, muscle mass, and muscle strength in relation to functional decline in older persons. *Epidemiologic Reviews.* 2013;35:51-65.