Fontys Paramedische Hogeschool

# Fontys Paramedic University of Applied Sciences

Physiotherapy, English Stream

Bachelor Thesis

# The relation between gait speed and knee adduction moment impulse during gait


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## Preface

Osteoarthritis is the most common joint disorder in the world. Frequently the knee is affected. Measures that investigate the load placed on the medial compartment of the knee have lately received more attention, especially the knee adduction moment impulse, which could be the most comprehensible variable for measuring knee load. This has inspired me to conduct further research in this field. During my four years of education at Fontys Hogescholen Eindhoven, I learned that not only individual clinical expertise but also the best available evidence of treatment makes an improved patient outcome possible. I wanted to execute a study, which might actually produce changes that are applicable in the field of physiotherapy in general, and gait retraining in particular.

This paper is primarily addressed to professionals in health care and human movement sciences interested in or working with patients that suffer from osteoarthritis. I hope that this study can help make more people aware of this this topic and hopefully further research is done about it.

Paul Herzeg
Eindhoven, 2nd of June 2014

## Abstract

**Background information.** Osteoarthritis in the knee usually starts in the medial tibiofemoral compartment. Estimations state that loads transferred through the medial compartment are 2.5 times higher than those transferred through the lateral compartment. Due to the fact that non-invasive in vivo measurements do not exist, medial knee load is usually measured by the external knee adduction moment, a measurement that is related to osteoarthritis progression. The knee adduction moment impulse, a proxy for knee load over time, might be the most comprehensive variable to measure knee load as it does not only take the magnitude of loading but also the duration of loading into account. This is important for gait retraining due to the fact that stance duration can be affected by gait speed.

**Objective**. The objective of the study was to determine whether or not there is a relation between KAM impulse and gait speed.

**Method**. In this experimental study, subjects' gait speed at five different categories was measured using a forceplate and a 3D system including cameras and markers. Measured data was exported to Visual 3D and then SPSS was used to find a correlation between knee adduction moment impulse and gait speed. Finally a regression analysis was performed.

**Results.** 20 healthy subjects were measured. A moderate and significant correlation of gait speed and knee adduction moment impulse was found. Knee adduction moment impulse was inversely related to gait speed.

**Conclusion.** Knee adduction moment impulse decreases with increasing gait speed. Patients should walk faster in order to decrease knee load during gait retraining. Nevertheless, future research, including both patients with osteoarthritis and healthy subjects, should be performed.

**Keywords.** Osteoarthritis; Knee adduction moment; Knee adduction moment impulse; Gait retraining

## Table of Contents

## Introduction

### Theoretical Background

Of all the joint disorders, Osteoarthritis (OA) is the most common one in the world (Arden & Nevitt, 2006). Radiographic evidence shows that in the Western population, the majority of people above 65 years and about 80% of people aged above 75 suffer from OA (Arden & Nevitt, 2006). Most often, OA is defined by joint symptoms, such as stiffness and pain, and structural pathology (Arden & Nevitt, 2006). This diverse joint pathology includes focal damage, loss of articular cartilage, abnormal remodelling and attrition of subarticular bone, osteophytes, ligamentous laxity, weakening of periarticular muscles, and in some cases synovial distension and inflammation (Hutton, 1989). Although the public health impact is enormous, the emergence of OA remains cryptic (Arden & Nevitt, 2006). Risk factors that affect the progression of OA can be divided into three groups, including hereditary contributions, mechanical factors and the natural effects of aging. (Goldring & Goldring, 2007). Obesity, joint instability, joint misalignment, increasing age, muscular weakness, peripheral neuropathy and associated intra-articular crystal deposition are considered to be factors that increase the chance of development and further progression of OA (Goldring & Goldring, 2007). Risk factors for developing OA can also be seen in close connection to 'normal loading' on 'abnormal cartilage' and 'abnormal loading' on 'normal cartilage' (Goldring & Goldring, 2007). The factor aging seems to be the primary trigger contributing to abnormal cartilage, although genetic factors that impair the function of the cartilage matrix can also be responsible for abnormal cartilage independent of aging (Goldring & Goldring, 2007). In the knee, OA very often affects the medial compartment (Hurwitz et al., 2002). There are theoretical estimations indicating that the loads transferred through the medial compartment of the knee are 2.5 times higher than those transferred through the lateral compartment (Schipplein & Andriacchi, 1991). The compressive load in the medial compartment is typically measured with the external knee adduction moment (KAM), which is obtained from a three-dimensional gait and video analysis, and acts as a valid and reliable surrogate measure for internal medial knee forces (Zhao et al., 2007). This is due to the fact that non-invasive in vivo measurements for medial compartment knee load are not yet available (Zhao et al., 2007). The M-shaped KAM waveform has two peaks during stance phase (Robbins & Maly, 2009). The first peak typically occurs during early stance and the second one during late stance (Robbins & Maly, 2009). The KAM curve looks similar to the M-shaped curve of the ventral ground reaction force (GRF).

Mechanical factors play an important role in structural progression of knee OA, in particular increased medial knee joint load (Sharma et al., 2010). Patients with tibiofemoral disease and knee varus alignment are three to four times more likely to progress to severe diseases than patients with more neutral knee alignment (Sharma et al., 2010). Due to knee varus alignment, the load-bearing axis shifts medial to the knee centre and therefore creates a bigger moment arm of the GRF, which in turn increases medial knee load and reduces lateral knee load (Sharma et al., 2010). The KAM is especially important in knee OA as it is related to a higher risk of obtaining structural disease progression (Miyazaki et al., 2002). The authors (Miyazaki et al., 2002) showed that for every 1%

increase in KAM peak, there was 6.5-fold rise in the risk of medial compartment disease progression on X-ray. Until lately the KAM peak, which typically occurs during the early stance phase, was seen as the most important KAM measurement to predict the progression of knee OA (Miyazaki et al., 2002). However, KAM peak does not take the duration of loading into account and solely measures the load at one instance of stance, while the KAM impulse, which is the integral of KAM over time, takes both, the magnitude of load and duration of loading into account (Kean et al., 2012). Thorp et al. (2006), who were the first ones to measure KAM impulse, showed that while both KAM peak and KAM impulse increased with radiographic disease severity, KAM impulse was the only one to differ between those with mild and moderate OA. Similar to these findings, Bennell et al. (2011) demonstrated that while a higher KAM impulse at baseline was associated with significantly greater loss of cartilage over 12 months, the same relationship could not be observed for KAM peak. Robbins and Maly (2009) concluded from their study that KAM impulse was more suitable than KAM peak to make a distinction between different subject groups that ambulate at different speeds, such as knee OA patients and healthy controls. Thorp et al. (2006), Bennell et al. (2011) and Robbins and Maly (2009) concluded that KAM impulse might be a more comprehensive indicator of knee load since it does not only take magnitude of loading into account but also load duration, which contributes to total knee load exposure. This was confirmed by loadbearing studies that showed that the effect of the time integral of load on the articular surface is as important as the effect of the load magnitude itself (Nuki and Salter, 2007). Hence, KAM impulse could be a more comprehensive unit for mechanical joint load than the KAM peak (Kean et al., 2012).

KAM impulse can, at least in theory, be reduced by lowering the magnitude of KAM, which is what gait retraining is usually aimed at. Furthermore, it can be diminished by reducing the duration of load, which can be influenced by gait speed. Research shows that individuals with knee OA tend to walk at slower speed, producing therefore longer stance phases when compared to asymptomatic individuals (Al-Zharani & Bakheit, 2002). This could be a good natural way of preventing OA progression as slower gait speed might reduce KAM peak (Robbins & Maly, 2009). However, it is hypothesized that a rise in duration of the stance phase, and therefore a rise in time under load, might result in an overall increase in joint loading (Kean et al., 2012). Consequently, lower gait speed seems to increase load duration (Kean et al., 2012). Currently it is known, that patients with OA have a higher KAM peak than asymptomatic individuals (Miyazaki et al., 2002). They tend to walk slower, have a shorter stride length and therefore a longer stance phase (Al-Zharani & Bakheit, 2002), which might lead to an increase in KAM impulse and hence an increase in joint loading (Kean et al., 2012). However, it is currently not known what the trade-off between gait speed and KAM impulse is. Therefore, in gait retraining, it is not known whether slow gait speed actually reduces KAM impulse.

**Problem definition**

Although the KAM impulse seems to be an important measurement for medial knee load, there are only few studies currently available that have investigated the relationship between gait speed and KAM impulse (Robbins & Maly, 2009; Thorp et al., 2006; Noort et al., 2013). Furthermore, to the knowledge of the author, there is no study available that investigates the correlation between gait speed and KAM impulse over the whole spectrum of walking speed. Therefore, it is not known what happens with the KAM impulse at high and low ends of gait speed and whether it constantly changes with changes in walking speed. This however, is important for gait retraining, due to the fact that patients walk slower during gait retraining (Gerbrands et al., 2014). This could be correct because it is hypothesized that KAM peak might be lower with slower gait speed (Robbins & Maly, 2009), which in turn would mean that also KAM impulse is lower. Nevertheless, if the dominant factor in KAM impulse is duration and not peak, the cumulative load of higher gait speeds and a subsequently shorter stance phase could be smaller than the cumulative load of lower gait speeds and a therefore longer stance phase. Hence, the hypothesis of this study is that KAM impulse is negatively correlated to gait speed, meaning that KAM impulse gets smaller with increasing gait speed. If no relation between gait speed and KAM impulse can be found, the KAM peak should still be regarded as the gold standard, and patients participating in gait retraining should keep on walking slower. If, however, the hypothesis can be proven right, and a negative correlation between gait speed and KAM impulse is found, a completely new insight into gait retraining of knee OA patients would be gained. In that case, patients that participate in gait retraining should be focusing on decreasing KAM impulse, which is coupled to stance duration and therefore gait speed, which should then be increased.

**Research question**

This leads to the question: What is the relation between gait speed and knee adduction moment impulse during gait?

## Methods

### Study design

The study was designed as an experimental study.

### Inclusion and exclusion of subjects

Subjects were recruited from Fontys University of Applied Sciences in Eindhoven. All included subjects had to be between 18 and 35 years old, healthy, active and able to speak and understand English. Participation was voluntarily. Subjects that suffered from actual knee OA, any gait impairment or any injuries to their lower limb, upper limb or spine region, that altered or impaired their gait pattern, were excluded from the study.

### Recruiting of subjects

On 17th of February 2014, students of Fontys University of Applied Sciences were recruited via e-mail (Appendix I) and later on via oral promotion. The subjects were informed about the testing procedure and possible risks orally and by an information letter (Appendix II). Participating subjects were informed that they had to sign an informed consent (Appendix III). They also received both, written and oral, information that their data will be stored for 5 years and other researchers conducting studies in a similar field will have access to it, although personal information of the participants will only be accessible to the researcher, the co-researcher and his supervisor (Appendix II).

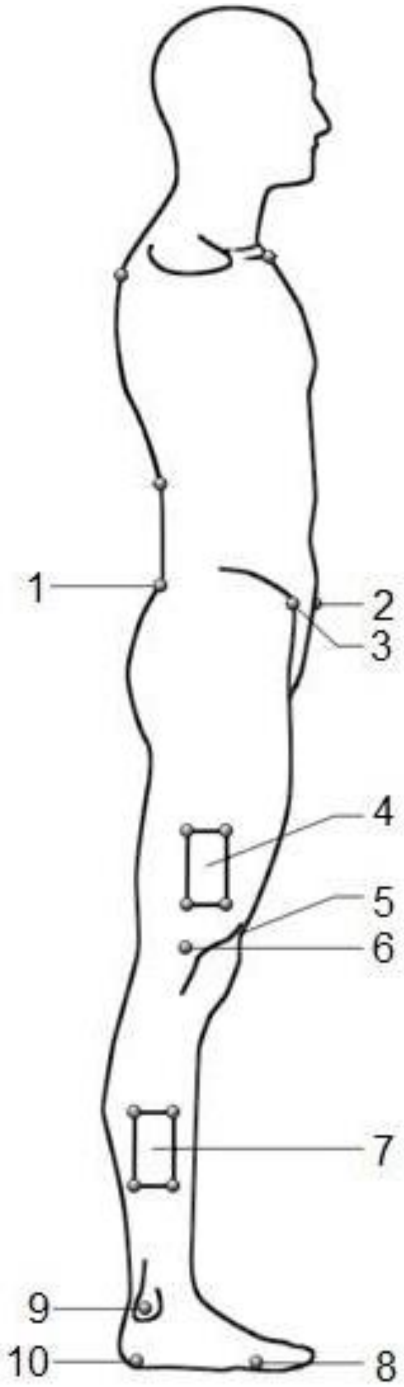
### Procedure of measurement

First the participants signed the informed consent (Appendix III). In order to make sure all subjects met the inclusion criteria, they had to fill in a questionnaire (Appendix IV). Then they changed to appropriate clothes (biking shorts, topless apart from a bra for females) so that marker visibility would be 100%. After that their height, length of their upper and lower leg and width of pelvis and knee were recorded and written down on a data sheet (Appendix V).

KAM was calculated from gait data collected from the subjects' right leg, using a three-dimensional motion analysis system. The system consisted of two cameras (Codamotion, CX1 (Charnwood Dynamics, Ltd.)) with a sample rate of 200 Hz, a recording system (Codamotion Analysis (Charnwood Dynamics Ltd)) and a synchronized floor mounted force plate (AMTI OR6-7 (Advanced Mechanical Technology Inc.)) with a sample rate of 1000 Hz. Eleven 3D markers were placed on the subjects' trunk and right leg according to Protocol 3D (figure 1). Subjects were first asked to stand barefoot on the force plate to determine body weight and provide a reference frame for gait analysis. Then the subjects started barefoot at a cone, which marked the starting point and was placed by the researcher, and walked at comfortable walking speed for 10 steps. At the same time, the researcher calculated the cadence for comfortable walking speed. Cadences per person, mean for male and female and mean overall cadence, were noted in a table (Appendix VI). After that the subjects were instructed to always start walking at the cone whenever they were ready. Again the cone was moved by the researcher to ensure a good starting position. The starting position was important because the subjects had to hit the force plate with the right foot being fully placed within its borders. The subjects did not receive instructions to hit the force plate in order to make sure that they did not aim for it. The participants walked barefoot across an 8m capture area and were given at least 1m to accelerate before and 1m to decelerate after the capture area. Then they walked five bouts at five different walking speeds in the following order: comfortable walking (1), very slow (2), slow (3), fast (4) and very fast (5). The researcher asked the subjects to walk to the beat of a metronome, which acted as help to facilitate different gait speeds over ground. The metronome was set according to the steps per minute the subjects were supposed to walk and was used to control for gait speed. A fixed number for cadence was used for walking condition 2 to 5, hence all the speed categories apart from comfortable walking. The walking cadences were set after a trial in which an uninvolved subject walked at comfortable, very slow and very fast walking speed. The remaining cadences (for slow and fast walking speed) were calculated from the already recorded cadences. The fixed cadences can be found in a table (Appendix VII). Furthermore, subjects were also asked to walk according to the feedback of the researcher, which was provided after each trial. Gait speeds were different from subject to subject due to different anatomical perquisites, such as body weight and height, leg length, pelvic and knee width. The researcher noted on a document which walking speeds had already been done and instructed the subjects to simply walk a little bit faster or slower, depending on which speeds had not been done yet. Five successful trials were recorded for each walking condition. Figure 2 presents a flowchart of the measuring procedures. A checklist for activities that were done in the movement lab can be found in attachment (Appendix VIII).

**Justification of measurement tools**

Both, the 3D gait analysis and the force plate measurements, are measurement instruments used by many researchers (Hurwitz et al., 2002; Miyazaki et al., 2002; Bennell et al., 2011; Kean et al., 2012 & Noort et al., 2013). Therefore, it can be stated that 3D gait analysis as well as force plates are the gold standards for measuring KAM and GRF. Research that has been conducted about the 3D measurement tool that will be used in this research, the Codamotion 3D-gait analysis, shows that it works best in a method based on resolution and light intensity (Schwartz et al., 2011). All measurement tools were provided by Fontys University of Applied Sciences.




| # | Marker placement |
|---|---|
| 1. | S.1 |
| 2. | Left ASIS |
| 3. | Right ASIS |
| 4. | Cluster marker upper leg |
| 5. | Medial femoral epicondyle |
| 6. | Lateral femoral epicondyle |
| 7. | Cluster marker lower leg |
| 8. | Caput metatarsal V |
| 9. | Lateral malleolus |
| 10. | Lateral calcaneus |
| 11. | Medial malleolus |

**Figure 1:** *Protocol 3D. 11 markers were placed on specific points (1-11) for the 3D gait analysis. S.1 stands for the top of the sacrum. Source: Tim Gerbrands.*

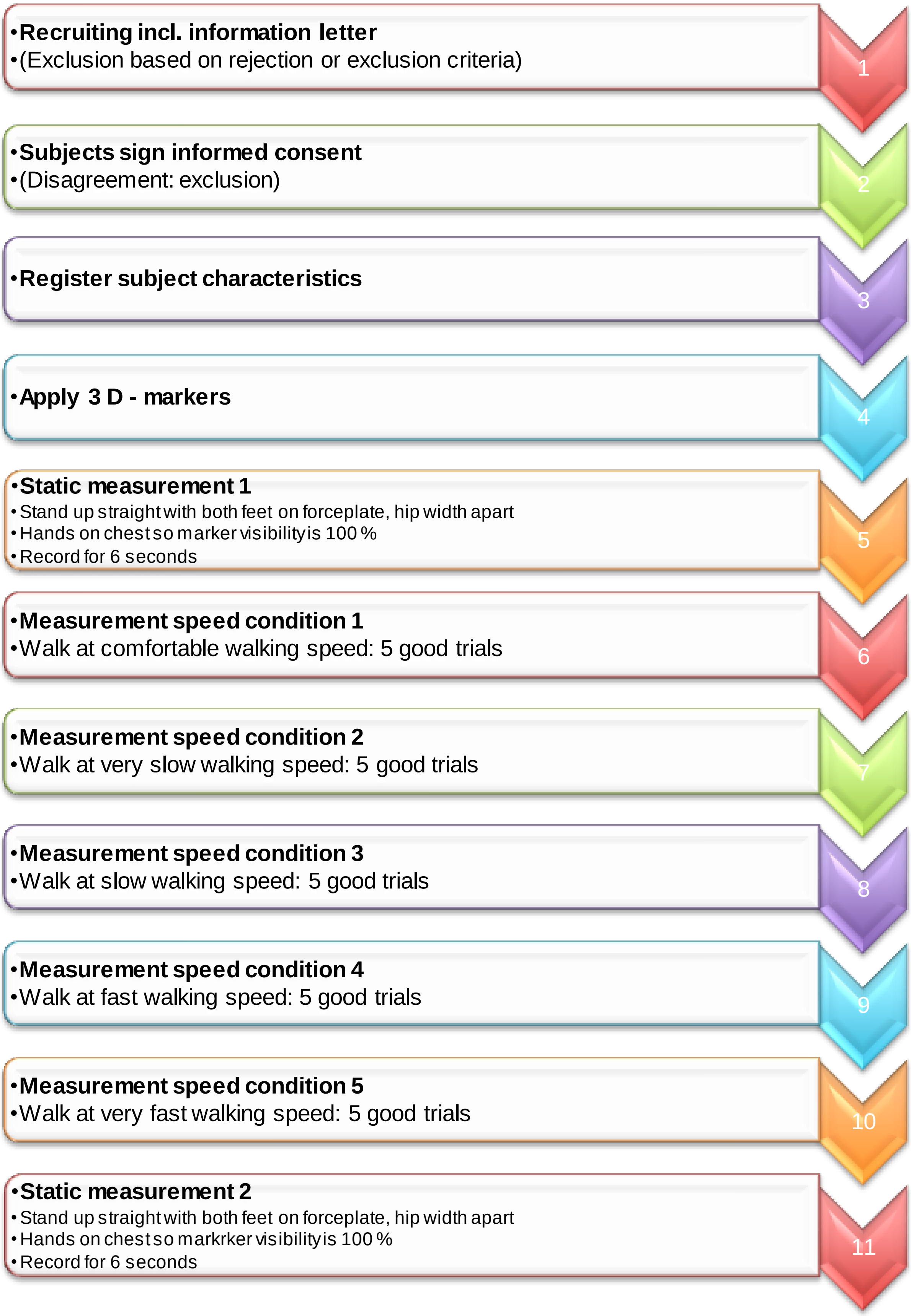



**Figure 2***: Flowchart of the measurement protocol. Flowchart including all the steps done.*

**Data analysis**

Kinematic and kinetic data were exported from Codamotion Analysis to Visual 3D (C-Motion), where a model (Davis et al., 1991) was applied to determine joint centres of the right ankle, knee and hip. The stance phase was defined by a threshold of 10N on the force plate´s vertical axis.

The KAM was calculated by means of inverse dynamics, taking into account the magnitude and direction of the GRF relative to the knee centre and the accelerations of the body segments. KAM impulse then was defined as the integral of KAM over time, meaning the surface area under the graph. KAM peak was defined as the maximal value of KAM.

**Statistical analysis**

For each participant a scatter plot was made between walking speed and KAM impulse. By the means of visual inspection, data outliers were sought for and potential deviants excluded. Using SPSS version 21 (Statistical Package for the Social Sciences; SPSS Inc., Chicago, IL), repeated measures ANOVA together with a Bonferroni post hoc test were implemented to find statistical differences of walking speed condition categories to each other. A p-value of 0.05 was considered as significant. If, after ANOVA, not all categories were distinct from each other, data was pooled and normalized to body weight times height, in order to increase the comparability between subjects.

A Pearson correlation coefficient (r) was calculated using SPSS. Correlations lower than -0.8 or exceeding 0.8 were interpreted as good, between 0.3 and 0.8 (or -0.3 and -0.8) as moderate, between 0.1 and 0.3 (or -0.1 and -0.3) as weak and between -0.1 to 0.1 as no correlation. A p-value of 0.05 was considered as significant. If a correlation was found, a simple linear regression analysis model was applied in SPSS, in order to find the predictive value of speed for KAM.

**Ethical aspects**

Due to the fact that the study design did not involve risks for the participants it was declared a non-WMO obligated study. This was approved by the MTEC (Medical Ethical Monitoring Committee) of the University Medical Centre Utrecht. Furthermore, the subjects were well informed by an information letter (Appendix II) and were asked to sign an informed consent (Appendix IV) prior to the testing procedure. During testing both researchers accompanied each participant at all times.

## Results

All subjects meeting the inclusion criteria were included in the study, which led to a total number of 20 participants (N=20) of whom 60 % were male (n=12) and 40 % female (n=8). The mean age was 23.75 (± 2,65, SD) years. Table 1 shows all descriptive data collected.

**table 1: Descriptive subject data rounded to 1 decimal**

| | **Mean** | **SD*** |
|---|---|---|
| **Bodyweight (kg)** | 75,5 | ± 18,7 |
| **Height (m)** | 1,8 | ± 0,1 |
| **BMI** (kg/m$^2$)** | 23,7 | ± 2,9 |
| **Thigh length (cm)** | 41,5 | ± 4,0 |
| **Leg length (cm)** | 42,0 | ± 4,5 |
| **Pelvic width (cm)** | 27,7 | ± 3,2 |
| **Knee width (cm)** | 10,0 | ± 1,4 |

**Standard Deviation, **Body mass index*

The mean overall cadence was 104,9 steps per minute for walking condition 1. Mean total speed was 1.12 m/s (±0.4 m/s, SD) and mean total KAM impulse 0.10 Nms/BwHt (±0.05 Nms/BwHt, SD). The different speed categories were well spread around the mean as can be seen in table 2, which displays the remaining means and SDs per speed category for KAM impulse and speed.

**table 2: Mean and SD of normalized results rounded to 2 decimals**

| | **KAM impulse Mean (SD) (Nms/BwHt)*** | **Speed Mean (SD) (m/s)** |
|---|---|---|
| **Very Slow** | 0,14 (±0,06) | 0,80 (±0.21) |
| **Slow** | 0,12 (±0,05) | 0,87 (±0.19) |
| **Comfortable** | 0,09 (±0,03) | 1,09 (±0,25) |
| **Fast** | 0,07 (±0,03) | 1,28 (±0,32) |
| **Very Fast** | 0,06 (±0,03) | 1,54 (±0,35) |

*Newton-meter-seconds/Bodyweight*Height

After visual inspection of the measured raw data, one subject's KAM impulse at very fast walking speed was found to be incorrect due to the loss of markers during the measurement procedure and was therefore excluded. Repeated measures ANOVA together with the Bonferroni post hoc test showed that all gait speed categories, based on different frequencies, differed significantly from each other (p=<0.05), except very slow and slow gait speed (p=0.164). As a consequence it was not possible to display data in categories but only in actual speed. Subsequently, the data was pooled and normalized to bodyweight and height. Figure 3 shows one random subject's data of the five gait speed categories and KAM over time. It represents a tendency for all subjects' M curves.

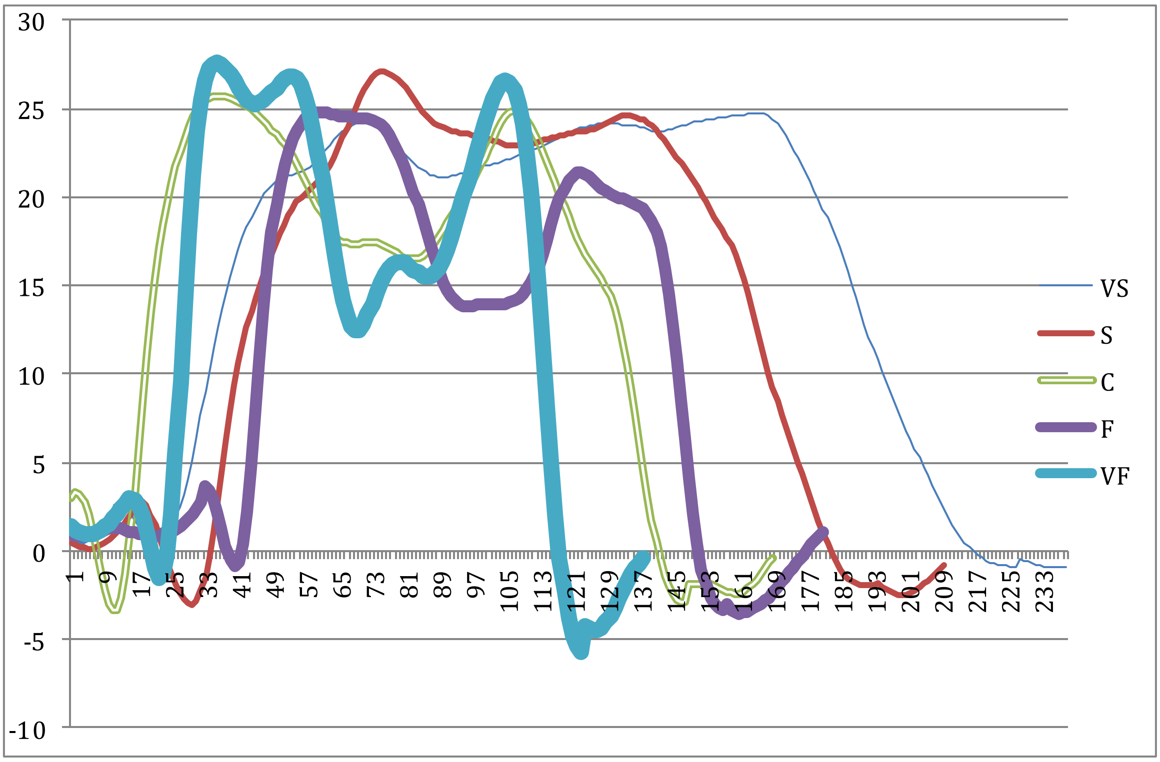



**Figure 3:** *This curve, which looks similar to that of the GRF, shows the KAM impulse (Nms) over time per speed category (VS = very slow; S = slow; C = comfortable; F = fast; VF = very fast). It can be observed that the integral underneath the curve decreases as gait speed increases. Due the fact that the data, used for this tendency curve, is not yet normalized, gait speed categories are displayed.*

There was a moderate and significant correlation (r= - 0.385, p=0.001) between gait speed and KAM impulse. KAM impulse is inversely related to speed. Data input for correlation and regression analysis is presented in Figure 4. The linear regression model was able to account for 14,8 % of the variance in KAM (F=16.84, p=0.001, $R^2$= 0.148), and presented an inverse relation between walking speed and KAM (B= - 0.51).

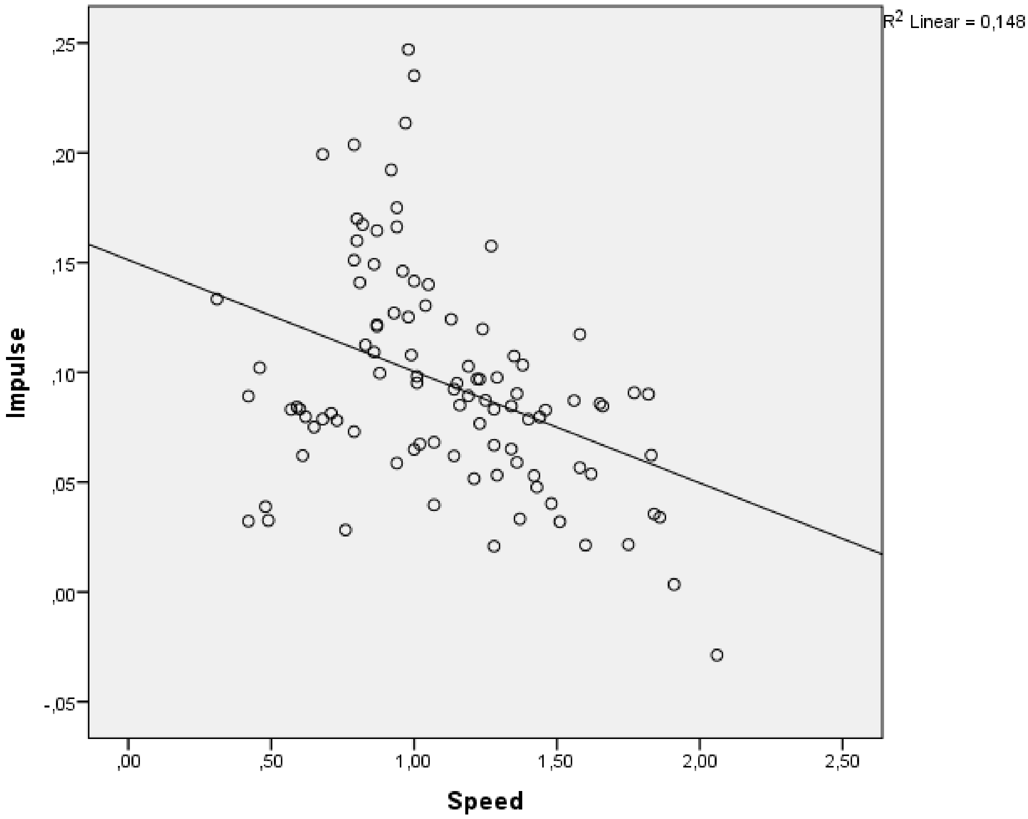



**Figure 4:** *Regression curve states KAM impulse (Nms/BwHt) versus gait speed (m/s). KAM impulse is inversely related (B=-0.51) to walking speed. Actual gait speed (m/s) was chosen for visualization due to the fact that not all the categories (1-5) differed significantly from each other.*

## Discussion

This study aimed to determine the relationship between gait speed and KAM impulse by measuring gait speed at five different conditions. The results showed that there was a moderate and statistically significant correlation between gait speed and KAM impulse. KAM impulse clearly decreased with increasing speed as can be observed in the regression curve (figure 4). Table 2 of the results section shows that gait speeds and KAM impulses were evenly spread around the mean, which justifies the choice to opt for linear regression when analysing data. By observing figure 3 in the results section, one can visualize that the integral of the curve, the KAM impulse, got smaller the higher the gait speed and the curve's width reduced respectively. Meanwhile the two KAM peaks almost stayed the same with different gait speeds (figure 3). Therefore, the author's hypothesis that KAM impulse would decrease with higher gait speed can be supported. This, however, was expected since KAM impulse takes both, stance duration and magnitude, into account and not just magnitude of load as the KAM peak does. Stance duration is naturally bigger at slower gait speed due to the longer time spend loading the knee and magnitude did not increase with gait speed. Therefore, the decrease in KAM impulse during faster gait speeds can be explained due to the fact that the knee was exposed shorter to medial knee joint loading duration and that KAM peak did not increase with higher speeds (figure 3). This current study had an interesting subject group and set-up. Young and healthy subjects from Fontys University of Applied Sciences were chosen in favour of actual OA patients. Due to that fact, the mean age of the subjects was only 23.75 years. This is lower than what can be expected to be the average age of actual OA patients, since OA, similar to most other degenerative diseases, usually develops in later decades of life. Although no radiographic images of the subjects' knees were taken, the author concluded that together with the age and answers obtained from a questionnaire (Appendix IV), the probability that the test subjects were suffering from OA should be zero. The difference in age and knee OA stage compared to actual OA patients does not change the applicability of the results of this study. The author of this study shares the hypothesis of Noort et al. (2013) that biomechanically the differences between an elderly population with knee OA and a young and asymptomatic subject group should not be significant. Given the fact that KAM peak, which is bigger in patients with knee OA (Miyazaki et al., 2002), is not correlated to gait speed (Hollmann, 2014), the only difference would be a longer stance phase in OA patients because they walk slower at baseline (Al-Zharani & Bakheit, 2002). Although the KAM impulse actually increases with disease severity (Thorp et al., 2006), there is no reason to believe that an increased KAM impulse of an actual OA patient at baseline will not decrease the same way as the KAM impulse of asymptomatic subjects did in this current study. However, as this cannot be stated with absolute certainty, the author of this study suggests that future research should focus on conducting a study that includes both OA patients and healthy subjects.

The set-up of this paper also needs to be discussed. Gait speed was not directly measured. The same study could be reproduced using a treadmill containing a force plate. However, the question is whether that would influence the results. Riley et al. (2007), who compared overground with treadmill walking in healthy subjects, showed that treadmill walking and overground walking are very similar. However, all GRF maxima were statistically significantly smaller ($p<0.05$) for treadmill versus over ground gait, as were 15 out of 18 moment, and 3 out of 6 power maxima. Although the authors (Riley et al., 2007) stated that walking speed, cadence and step length were more constant on a treadmill than for overground walking, they also found that treadmill belt speed was exposed to small decreases due to belt slip on the drive rollers of the treadmill. This was thought to be the reason for different peak knee extension moments (Riley et al., 2007). Although the authors (Riley et al., 2007) stated that these differences would be within the normal variability of gait parameters, it can be suggested that these differences might be bigger at other treadmills due to even more belt slip. Furthermore, Riley et al. (2007) stated that analysis of treadmill gait would be functionally equivalent to evaluating overground gait in healthy subjects that are used to treadmill walking. Therefore, it can be concluded that although it is easier to control for gait speed and cadence and step length are more constant on a treadmill than over ground, gait speed might not be constant after all due to belt slip and subjects that are not acquainted to treadmill walking may need time to get used to it. Additionally, to the knowledge of the author, no study has yet compared treadmill walking with overground walking when measuring KAM impulse by using a 3D gait analysis system and a force plate. Therefore it cannot be stated that treadmill testing would be a better option than over ground testing and it can be suggested that the measured results in this current study were not negatively influenced by the fact that the experiment was conducted overground instead of on a treadmill. Future research is needed to find out whether KAM impulse measurements are different on a treadmill when compared to over ground walking.

**Clinical implications**

Since the results of this paper showed that higher gait speed decreases KAM impulse and therefore medial knee load, the question arises whether the concept of gait retraining should be rethought and renewed. Gait retraining is a strategy to lower mechanical loading on the affected compartment and thereby decrease pain and further OA progression (Simic et al. 2010; Miyazaki et al. 2002 & Bennell et al. 2011). Common gait retraining modalities often include reduction of walking speed, a toe-out foot position and medio-lateral trunk sway (Noort et al., 2013). Reduction in walking speed originates form the suggestions of some researchers (Mündermann et al., 2004) that this would be an effective gait retraining strategy to reduce knee load. Interestingly, other gait retraining strategies, such as a toe-out foot position and medio-lateral trunk sway, are often accompanied by a loss in gait speed (Gerbrands et al., 2014). Among others, Mündermann et al. (2004) have suggested that patients with less-severe OA would benefit from reduced walking speeds as it was found to reduce the KAM peak in their study. However, these patients would also be exposed to a longer loading duration in the medial knee compartment, which would increase KAM impulse. The question that arises is why Mündermann et al. (2004) found a positive correlation between walking speed and KAM peak, for all but one patient with less severe OA, while the current findings found a negative correlation between walking speed and KAM impulse. If load duration decreased similar in the study by Mündermann et al. (2004) as it did in the current paper, then the trade-off between increasing KAM peak and decreasing load duration determined the impulse. Hence, given the current findings of this study, loading duration is dominant to KAM peak. Additionally, the findings of Hollmann (2014), who used the exact same patient dataset as this current paper, do not support the past findings of Mündermann et al. (2004) and show that KAM peak does not increase with gait speed. Furthermore, training slower gait speeds could also have adverse effects on overall physical functioning, daily tasks and safety (Simic et al., 2011). Therefore it may be concluded, that reducing walking speed is not an option to decrease OA progression. Especially, since increased KAM impulse is related to disease progression of knee OA (Bennell et al., 2011). Although increased toe-out foot position did result in early-stance KAM peak changes ranging from a 55,2% reduction to an increase of 12,9% (Simic et al., 2011) and medio-lateral trunk sway gait led to an average reduction of 65% of early-stance KAM peak (Mündermann et al., 2008), the effects on back load and especially walking speed could be detrimental (Noort et al., 2013). Walking in a different gait pattern that does not come naturally to the patient can be quite a challenge in regards to coordination. Hence, it is logical that not all patients participating in gait retraining can keep up the same speed when walking a different kind of gait compared to their normal gait. A study by Barrios et al. (2010) showed that walking in a specific and complex gait pattern (hip internal rotation and adduction) is rather difficult for patients to perform. Although the subjects stated that both perceived effort and naturalness improved, they still found it difficult to maintain the newly adapted walking style after 8 sessions. Hence, it can be concluded that obtaining a new gait modality is difficult for patients and could have detrimental effects amongst others on walking speed. Therefore it can be suggested, that gait retraining strategies should be rather easily obtainable and maintainable and most importantly not have a detrimental effect on walking speed. Future research should focus on assessing which gait retraining strategies, next to simply walking faster, are the easiest to obtain and maintain and at the same time do not have a detrimental effect on walking speed. Another possible cause why patients cannot keep the same speed when walking in a different way could be that physicians, who instruct patients during gait retraining, simply do not give the right instructions and feedback in order to make sure that speed is kept at the same level or that the speed even increases. Most importantly though, it is known that OA patients tend to walk at slower speed, producing therefore longer stance phases when compared to asymptomatic individuals (Al-Zharani & Bakheit, 2002). So even if OA patients do not walk slower when participating in gait retraining, they still walk slower than healthy subjects (Al-Zharani & Bakheit, 2002) at baseline. Therefore, the author of this study suggests that increasing gait speed should be a gait retraining strategy by itself, as simply walking faster is safe and easily obtainable. It clearly decreases KAM impulse and as Hollmann (2014) showed it does not, opposite to previous knowledge, increase KAM peak. Whether gait-retraining strategies such as medio-lateral trunk sway or increased toe-out foot positions in combination with faster gait speed could decrease medial knee compartment load even further, has to the knowledge of the author, not yet been assessed. A study by Gerbrands et al. (2014) showed that during medio-lateral trunk sway gait, the gait speed loss was significant when compared to normal walking. This is interesting, since it also decreases KAM peak (Mündermann et al., 2008). Therefore the question arises what the effects of walking slower, as a result of medio-lateral trunk sway gait, were. It can be hypothesized that, if KAM peak decreased although stance duration increased due to slower gait speed, the benefits of gait retraining could have been even bigger if the patients would have walked faster in combination with medio-lateral trunk sway gait. Therefore the author of this study suggests that medio-lateral trunk sway gait might be even more effective if patients were to walk faster. However, as this is only a hypothesis, future research should focus on testing whether that is the case.

Additionally, it would be desirable to conduct a study that focuses on gait retraining by increasing gait speed and that includes a follow up in order to compare the progression of OA of a patient group to a control group. Until this is clear, the author of this study suggests, that physicians who retrain patient`s gait, should always instruct patients to walk faster. They should rather be focusing on reducing KAM impulse than KAM peak. Due to the fact that often physiotherapy facilities have a treadmill but do not have enough space to conduct gait retraining overground, it can be suggested that it is easier for physical therapists to let patients participate in gait retraining on a treadmill. In that way physical therapists can also more easily control for gait speed. However, the question that remains is how fast patients should walk. This question is rather difficult to answer. Firstly it should be stated that there is no given speed that physicians participating in gait retraining should aim to reach with their patients. Each patient group is different from another and so are their abilities and limitations. Due to the fact that most subjects that participated in this study had difficulties in keeping up the same speed in the very fast walking condition (1,54 m/s (±0,35 m/s)) for a distance of 8m, it seems impossible that actual OA patients would be able to walk very fast for a longer amount of time without detrimental effects to safety and daily functioning. Furthermore, walking at very fast speed places a too high burden on the patients' endurance and strength. Physicians that are training patients should let them walk faster than their comfortable walking speed but not too fast, so that it does not become unnatural and unsafe. If that should not be possible, physicians should pay attention that patients at least keep their speed and do not walk slower, as this would increase stance duration. However, it has to be said that no general answer on this topic can be given and therefore future research is needed.
Another clinical implication that can be withdrawn from the results of this study is that KAM impulse should no longer be undervalued when compared to KAM peak. The findings of this current study showed that KAM impulse was inversely related to gait speed. At the same time, the co-researcher of this study Hollmann (2014) could not present a statistically significant correlation between gait speed and KAM peak. Conversely to numerous previous findings (for example Robbins & Maly, 2009) in the same fields, Hollmann (2014) could not state that KAM peak did increase with higher gait speeds. Hence, it can be suggested that KAM impulse is a better value for measuring knee load in daily practice, although KAM peak cannot be neglected, as joint loading is a combination of both magnitude of KAM and loading duration. Both values are important to the understanding of knee joint loading and should be divided into two categories. KAM peak represents a value that is required when talking about acute trauma. Hence if there is a high peak then there will be damage to the cartilage. KAM impulse on the other hand is required when talking about joint loading over a long period of time. Hence, if loading duration was really long and/or if KAM peak was huge. From the findings of this study it can therefore be concluded, that KAM impulse should be considered to be the gold standard unit for external knee loading measurement when a load over time measurement is required as KAM impulse presents the more comprehensible measurement, when compared to KAM peak. At the same time, KAM peak cannot be neglected, as it is an important during high impact measurements.

**Comparison to literature**

Investigating the relation between KAM impulse and gait speed has, to the knowledge of the author, only been done by very few studies before, namely by Robbins and Maly (2009), Noort et al. (2013) and Thorp et al. (2006). A study that compared gait speed and the changes in KAM impulse is the one of Robbins and Maly (2009). The authors (Robbins & Maly, 2009) found that a decrease in gait speed resulted in an increase in KAM impulse. Using a similar set up as this current paper they examined changes in KAM peak and KAM impulse in response to controlled changes in gait during over ground ambulation. The 34 young and asymptomatic subjects with a mean age of 32 (±8) years first walked at a self-selected gait speed before they had to walk faster and slower, which is similar to this current study, although this current paper had 2 more walking speeds (very slow and very fast). This makes the KAM impulse measurement of the current study more reliable due to the bigger variance of gait speed. The similar methods of the two papers make the results comparable. Therefore, the two studies complement each other in the conclusion that KAM impulse decreases with increasing speed.
Another study, conducted by Thorp et al. (2006), found that KAM impulse was negatively correlated with gait speed during both midstance and terminal stance phase and KAM peak was negatively correlated with gait speed in terminal stance. Basically, Thorp et al. (2006) found the same results as this current study. They measured 117 subjects of whom 28 were asymptomatic, 66 had mild OA and 23 had moderate OA. The overall age range for their subjects was between 32 and 85 years. This is quite interesting as their subject group is different from the one of this current paper, which performed measurements on young and asymptomatic subjects. Given the findings of Thorp et al. (2006), it can be suggested that the current findings of this study are similar to what can be expected in other study populations, especially in OA patients. A study by Noort et al. (2013) aimed to investigate the effect of walking speed, foot positioning, and trunk sway on 3D knee loading. Noort et al. (2013) had findings that were distinct from the ones of this paper and the ones of Robbins and Maly (2009). Although Noort et al. (2013) used a very similar subject sample size as this current paper and the one of Robbins and Maly (2009), namely 14 young and healthy subjects with a mean age of 23.8 years, they found that KAM impulse increased at fast walking speed, despite an observed decrease in stance duration during faster ambulation. This finding is interesting because it contradicts the results of this current study, which found a decrease in KAM impulse with fast walking speed. Therefore, the question arises why the findings are distinct from each other, given the similar subject population. Noort et al. (2013) let their subjects walk barefoot on a 10m walkway, near identical conditions to the setup of this current paper. However, Noort et al. (2013) only made use of 3 different walking speeds, namely self-selected, slow and fast walking speed, while this current paper used 5 different ambulation speeds, which represent a bigger variety of speeds. Both studies used a force plate of the same manufacturer, but Noort et al. (2013) made use of a different optoelectronic marker system (OptoTrak 3020, Northern Digital Instruments, Waterloo, Canada). Whether the slightly different gait lab set up in combination with a difference in walking speeds could be the cause for the differences in findings is unlikely, however, impossible to conclude with certainty. Interestingly Noort et al. (2013) also found that KAM peak increased in early and late stance phase. These findings are distinct from the ones of Hollmann (2014), who investigated the relation between gait speed and KAM peak and

could not present any statistically significant findings in his study. Hollmann's (2014) measurements, which were obtained from the exact same dataset as this current paper, showed a non-significant correlation (r=0.10, p=0.922) for KAM peak and gait speed. Hence, the question arises why there was a distinct finding for the KAM peak gait speed relation. The variance in gait speed conditions used for this current paper and the one of Hollmann (2014) was bigger with five gait speed categories, while Noort et al. (2013) only used three gait speed categories. The gait speed categories of Noort et al. (2013) were self-selected, 0.20 m/s slower than the self-selected speed for the slow walking speed category and 0.20 m/s faster than the self-selected speed for the fast walking speed category. Hence, gait speed categories were not set and subjects had to simply walk slower or faster than the comfortable walking speed. The range of mean walking speeds of Noort et al. (2013) was 1.17±0.04 m/s to 1.59±0.03 m/s. This is different from the range of mean walking speeds found in this current study, which was 0.80±0.21 m/s to 1.54±0.35 m/s. This presents a much bigger range of walking speeds than the range of walking speeds of Noort et al. (2013). The mean for the slowest walking speed (1.17±0.04 m/s) of Noort et al. (2013), which marked the lowest point on their gait speed range, was in between the mean comfortable (1.09±0.25 m/s) and mean fast walking speed (1.28±0.32 m/s) of this paper and therefore much faster than the mean for the slowest walking speed (0.80±0.21 m/s) used in this current study. Therefore, the author of this study hypothesizes that the differences in the gait - KAM correlations were due to the smaller range of gait speeds in the study of Noort et al. (2013). The walking speed range of Noort et al. (2013) did not reflect the whole range of normal walking, while the range of walking speeds of the current study did. Furthermore, it can be hypothesized, that the increase in KAM peak at faster walking speed in the study of Noort et al. (2013) is likely to be the cause of the increase in KAM impulse at higher speeds in their study. This can be seen in close connection to the fact that both findings of Noort et al. (2013), for KAM peak and KAM impulse, are different from the findings of both, this current study and the study Hollmann (2014). However, it has to be stated that this is only a hypothesis and the question arises whether the difference in the range of gait speeds is the only reason for the vastly different findings of the two studies. Therefore, further research on the relation between KAM impulse as well as KAM peak and gait speed is needed.

The findings of this study, that KAM impulse is inversely related to gait speed, have been supported by other studies (Thorp et al., 2006 & Robbins & Maly, 2009), although one study (Noort et al., 2013) found opposed results. In conclusion, it may be suggested that based on the results of this study KAM impulse is negatively correlated to gait speed and therefore knee load is lowered when gait speed is increased. However, due to the fact that Noort et al. (2013) had different findings, this cannot be stated with certainty and hence further research is needed to back up the results of this study or the ones of Noort et al. (2013).

**Study design limitations**

This study also had one limitation that needs to be discussed. Knee load was not measured directly on the articular surfaces but calculated using inverse dynamics and presented as the external KAM impulse. This was due to the fact that there is no non-invasive direct in vivo measurement of knee load yet available. Very recent research by Shinya et al. (2014), who investigated the relation between

KAM peak and actual medial knee contact force using a musculoskeletal model based simulation, showed that the first peak of the medial knee contact force could be predicted on the basis of the first peak of the KAM peak in normal gait in older people. Although this could be a pioneering finding, the authors also stated that muscle co-contractions of mainly the quadriceps and hamstrings muscles could yet change medial knee contact force (Shinya et al., 2014). Since these co-contractions were not included in the study of Shinya et al. (2014) it cannot be said with certainty that these predictions can be interpreted cautiously. Therefore, future research on the improvement of such musculoskeletal model based measurements for knee load is needed. However, it has to be stated that the research of Shinya et al. (2014) is a big step in the right direction to finally make results, obtained from measuring different subject groups, such as actual OA patients, older patients, obese patients and healthy patients, directly comparable.

## Conclusion

A moderate correlation between gait speed and KAM impulse, which is a proxy for loading in the medial compartment of the knee, was found in this study. KAM impulse decreases with increasing gait speed. KAM impulse should be considered to be the gold standard for measuring medial knee load over time. In practice, walking faster than the comfortable walking speed but not too fast so that it remains feasible for patients to obtain and maintain, should be considered to be a gait retraining option. However, it would be desirable to conduct a similar study including actual OA patients and a study that tests the hypothesis that simply walking faster is an effective gait retraining modality.

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## Appendices

### I Email to students

Dear student,

As you will probably know the 4th year students are currently preparing their thesis projects.

I, Paul Herzeg, will do a research in the Fontys gait lab about the relationship of gait speed and knee adduction moment impulse.

It is a really interesting project to participate in, especially since I am the first one ever to do these specific measurements. Furthermore, it will also be a little preparation for your own thesis project.

There are no risks involved and all you have to do is spare me 2 hours of your time and walk a bit.

The research will take place in the time between March and April 2014 and I will try to be as flexible as possible in order to make sure that you can participate.

Please read the information letter in the attachment and fill out the questionnaire if you are interested in participating.

Please let me know before the 15th of March if you want to participate.

I would be very happy to hear from you and welcome you in my study!

In case of any questions feel free to contact me.

Greetings,

Paul Herzeg
p.herzeg@student.fontys.nl
0641 228788

## II Information letter

Graduation research project

Knee adduction moment impulse – information letter

Dear student,

I, Paul Herzeg, 4$^{th}$ year student, would like to invite you to participate in my study that measures the knee adduction moment impulse.

In order to find out whether you want to participate please read this letter carefully. It should answer most your questions. If you have any additional questions please do not hesitate to contact me. You can find my contact details at the end of this letter.

What is the purpose of this research?

Osteoarthritis (OA) in the knee usually starts in the medial tibiofemoral compartment. Its progression is shown to be related to increased knee adduction moment (KAM) peaks during gait. This is logical because higher peaks lead to higher pressure, which then again increases the load that is placed on the cartilage. However, I think that it is also important how long you put high load on the medial knee and therefore think that KAM impulse might be a better measurement tool to predict progression of OA. Therefore I will try to find out how KAM impulse is related to gait speed in my study. Since this measurement has never been conducted before it is ground breaking information that can be used in everyday work of a physiotherapist.

What is happening during the research?

I would like to measure the effect of gait speed on KAM impulse. Therefore, the subjects will walk on different gait speeds chosen by the researcher. The measurements take place in the gait lab and will cost about 1 hour of your time. First your body height, weight, upper and lower leg length, pelvic and knee width will be measured. Using a force plate measurement and a 3D measurement you will be wired with 14 markers mainly on your lower limbs and thorax. After an initial static measurement you will then walk a couple of times over the force plate at different speeds.

Who can participate in the research?

Everyone that is between 18 and 35, healthy and studies at Fontys can participate. However, there are some exclusion criteria. Since this study is mainly about walking subjects that have any injuries that alter their gait pattern or actually have OA cannot be included. If you are not sure whether you are applicable please contact me and I will verify your application.

Are there any potential risks?

There are no risks connected with this study. Since you are walking in a controlled environment at normal walking speeds the chance of sustaining an injury is almost zero. There is always a researcher and supervisor in the gait lab in case you have any questions or need any assistance.

Furthermore, I want to make it clear that you can withdraw your participation at any time without stating any reason. Your participation is entirely voluntarily. Even after the research has been conducted you can still decide to step back and your data will be deleted.

Why should I participate?

First and foremost you would contribute to new insights and development in the prevention of progression of OA.

It will be advantageous for you to participate in a thesis project at least once in order to make sure that you know how a thesis project is built up and what you will do at the end of your studies.

There are no costs that come along with participating. Since the trial will take place at the Fontys gait lab you do not need to travel longer than you would usually to get to university.

I will provide you with snacks during the testing procedure.

What are disadvantages of participating?

The only thing one might consider as a disadvantage is that it will take 1 hour of your time.

What happens with the data?

The data will be handled anonymously and cannot be traced back to you. The measured data will be analysed and used for this thesis project. It will be available for 5 years after the publication of this research to other researchers. However, the personal data will be coded and therefore anonymous. Only the researcher and his supervisor have the full access to your data.

Do you have any questions left?

In case that this letter did not answer all your questions please feel free to contact me. In case you want to contact the supervisor of this research project or the coordinator of al research projects you can find their contact details below.

I hope to hear from you and welcome you in my research!

Greetings,

Paul Herzeg

Contact information

Researcher:
Paul Herzeg
p.herzeg@student.fontys.nl
0641228788

Supervisor:

Tim Gerbrands
t.gerbrands@fontys.nl
0623381440

Coordinator
Anke Lahaije
a.lahaije@fontys.nl
0620935802

## III Informed consent

Participation agreement in the study 'Knee adduction moment impulse – the most powerful unit for feedback on knee load?'

Herewith I declare that I agree with the following statements.

I have read the information letter and was able to post any possible questions and got them answered. I feel myself fully informed about the testing procedure and possible dangerous situation.

I had enough time to think about my participation. I declare that my participation is completely voluntarily. I know that I can withdraw my participation at any time without giving a reason why.

I agree that in the highly unlikely case of an injury the conductor of this research cannot be held responsible.

I agree that my personal data will be applicable to the people mentioned in the information letter. My data will be stored for 5 years on an anonymous basis. I agree that my data can be used for further research and other aims that are described in the information letter.

I agree to participate in the research.

Name test person:

Signature: Date: __/__/__ (DD/MM/YY)

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I herewith declare that I have fully informed the participating people about the testing procedure.

In the unlikely case that there should be anything that could change the participation agreement I will inform the affected people in time.

Paul Herzeg (Researcher)

Signature: Date: __/__/__ (DD/MM/YY)

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## IV Questionnaire participating students

Name:

Date of birth:

Gender:

Weight:

Height:

Do you suffer from any injuries that could possible alter your gait pattern? (If yes, what?)

Do you have osteoarthritis?

Do you take any medication?

If you have any questions concerning this questionnaire please contact Paul Herzeg (p.herzeg@student.fontys.nl, 0641228788)

I herewith declare that I have answered all this questions veritable. I know that answering questions incorrectly will jeopardize the outcomes of this study.

Name:

Signature: Date: __/__/__ (DD/MM/YY)

## V Data sheet

| | |
|---|---|
| **Name** | |
| **Date** | |

| | |
|---|---|
| **Sex (f/m)** | |
| **Birth date** | |
| **Body weight (kg)** | |
| **Body height (m)** | |
| **Length upper leg[1] (m)** | |
| **Length lower leg[2] (m)** | |
| **Pelvis width[3] (m)** | |
| **Knee width[4] (m)** | |

[1]) Trochanter major – Epicondylus femoris lateralis

[2]) Epicondylus femoris lateralis – Malleolus lateralis

[3]) SIAS – SIAS

[4]) Epicondylus femoris lateralis – Epicondylus femoris medialis

## VI Measured cadence per subject

**Table 'Measured cadence per subjects at comfortable walking speed (in steps per minute)'**

| Subject number | CStp per minute* | Mean male | Mean female | Mean overall |
|---|---|---|---|---|
| **1** | 96 | 101,8333333 | 109,5 | 104,9 |
| **2** | 98 | | | |
| **3** | 110 | | | |
| **4** | 105 | | | |
| **5** | 117 | | | |
| **6** | 105 | | | |
| **7** | 113 | | | |
| **8** | 107 | | | |
| **9** | 103 | | | |
| **10** | 110 | | | |
| **11** | 96 | | | |
| **12** | 105 | | | |
| **13** | 100 | | | |
| **14** | 101 | | | |
| **15** | 103 | | | |
| **16** | 117 | | | |
| **17** | 117 | | | |
| **18** | 110 | | | |
| **19** | 103 | | | |
| **20** | 82 | | | |

**Comfortable Steps per minute*

## VII Defined Speed conditions

**Table: Defined speed conditions**

| Speed | Steps per minute |
|---|---|
| **Speed condition 2 (Very Slow)** | 66 |
| **Speed condition 3 (Slow)** | 80 |
| **Speed condition 4 (Fast)** | 130 |
| **Speed condition 5 (Very fast)** | 160 |

## VIII Checklist for movement lab activities

Procedure in the movement lab

| # | Necessities |
|---|---|
| 1. | 3D-marker system: charged and prepared with double sided tape |
| 2. | Calibrate 3D-system |
| 3. | Calibrate Forceplate |
| 4. | Appropriate clothing |
| 5. | Informed consent |
| 6. | Information letter |
| 7. | Data Sheet |

---

| # | Preparation with patient |
|---|---|
| 1. | Sign the Informed Consent |
| 2. | Wear appropriate clothing |
| 3. | Fill in the Data sheet |
| 4. | Apply 3D-markers according to **PROTOCOL: 3D** |
| 5. | Test the marker application and Forceplate in a Live View |
| 6. | Continue to **PROTOCOL: Measurement Protocol** |

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**PROTOCOL: Measurement Protocol**

| Trial type | Activity | Trial name |
|---|---|---|
| Static measurement | - Stand up straight<br>- Both feet on Forceplate<br>- Hands on chest so marker visibility is 100%<br>- Record for 6 seconds | Static_pre |
| | | |
| | RANDOMISE THE SPEED CONDITIONS THAT ARE TO BE APLLIED | |
| | | |
| Walking conditions | Subjects will walk 5 times at 5 different speeds. The range of gait speeds is very slow, slow, comfortable, fast, very fast. Through oral comments by the researcher the participants will be instructed to either a little bit slower or faster until the whole | VS 1-5<br>S1-5<br>C1-5<br>F1-5<br>VF1-5 |

| | | |
|---|---|---|
| | range of gait speeds is covered. | |
| | | |
| Static measurement | - Stand up straight<br>- Both feet on Forceplate<br>- Hands on chest so marker visibility is 100%<br>- Record for 6 seconds | Static_post |

**Figure:** *Procedure in the gait lab. Necessities, preparation with the patient and actual measurement protocol. Source: Tim Gerbrands.*