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Is the medio-lateral pelvic displacement the prime determinant of the mechanism that keeps the EKAM constant at all walking speeds?

Bachelor Thesis

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Abstract

Background information. The knee is the joint most affected by osteoarthritis and its medio-lateral load distribution while walking is represented by the external knee adduction moment (EKAM, i.e. ground reaction force (GRF) times its moment arm). Although the GRF increases linearly with walking speed, research shows that the EKAM still stays constant. The reason for this is not clear yet. Understanding this mechanism could add value to treatment and prevention of osteoarthritis. The medio-lateral pelvic displacement (mlPD) might be related to the length of the moment arm and have a negative correlation with speed. The objective of this study was to find out whether the mlPD could be the prime mechanism to keep the EKAM constant at all walking speeds.

Method. Nineteen healthy subjects were tested with 3D gait analysis while walking at least ten times from the individuals' slowest to fastest speed. The correlations between mlPD and speed, GRF and speed as well as EKAM and speed were statistically analysed.

Results. No correlation and no statistical significance were found between mlPD and speed ($r = 0.006$, $p = 0.921$). The GRF showed a moderate, positive and statistically significant correlation with speed ($r = 0.516$, $p < 0.001$) and the EKAM peak presented a low and also statistically significant correlation with speed ($r = 0.329$, $p < 0.001$).

Conclusion. The mlPD is not the prime determinant keeping the EKAM constant at all walking speeds. However, a third of the study population showed a negative correlation between mlPD and speed. Therefore further research is needed to clarify under which circumstances the mlPD might work and to what extend it could be used for treatment and prevention. Maximal gait speed might provoke a correlation between EKAM and speed.

Keywords

Osteoarthritis, external knee adduction moment, medio-lateral pelvic displacement, pelvic sway

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Introduction

Osteoarthritis (OA) is one of the most common chronic pathological conditions (Bijlsma et al., 2011). The impact on health care and on the public health system is growing with the rising number of OA patients in the future (Lawrence et al., 2008). This can be related to the general ageing of the population, since OA prevalence increases with age (Van Saase et al., 1989). A survey of 10,412 OA patients showed that consequences arising from this pathology are quite extensive, as four out of five patients report problems with activities in their daily lives (Fautrel et al., 2005).
The joint that is most commonly affected by OA is the knee. In The Netherlands for example 15% of the general population suffer from symptomatic knee OA (Tukker et al., 2008) and 80% of the middleaged population from radiographic knee OA (Van Saase et al., 1989). Risk factors for knee OA in older adults are said to be primarily mechanical factors such as intense physical activity, previous knee injury and obesity (Cooper et al., 2000) as well as certain physical occupations that include kneeling and squatting (Coggon et al., 2000). There is evidence that the loads transferred through the medial compartment of the knee during gait are 2.5 times higher compared to the lateral compartment (Schipplein and Andriacchi, 1991) and that a varus knee alignment (decreased tibiofemoral angle) increases the risk of medial compartment OA progression (Sharma et al., 2001).

To evaluate the loading of the medial compartment dynamically, the external knee adduction moment (EKAM) is often used. It is calculated as the ground reaction force (GRF) times its moment arm, which is the shortest distance from the knee center to the GRF vector. It can be measured during walking by three-dimensional (3D) gait analysis and is a valid as well as reliable indication of the medio-lateral load distribution during gait (Shipplein, O.D. & Andriacchi, T.P., 1991; Zhao et al., 2007). Nevertheless, it is still being discussed to what extend the EKAM represents the medial contact force as Walter et al. (2010) presented in their study. However the importance of this experiment is weakened, since only one subject was included who additionally was no longer part of the OA population due to a knee implant. A study by Miyazaki et al. (2002) showed that an increase of the EKAM by 1% corresponds to a raised risk of aggravation of knee OA by 6.46 times, hence a prediction of radiographic OA progression can be made. As a consequence, patients with a higher severity of knee OA show a greater EKAM and an increased varus angle than patients with milder forms of OA (Mündermann et al., 2005). Therefore, since in vivo measurements are not feasible in daily clinical practice, the EKAM is a surrogate measure for predicting the medial contact force on the knee during the whole stance phase (Kutzner et al. 2013).

Researchers have tried to find treatment methods to decrease the EKAM peak and / or impulse (the integral of the EKAM) while walking by gait retraining (Mündermann et al., 2008; Simic et al., 2011; Simic et al., 2012; Gerbrands et al., 2014). This treatment strategy implements postural changes into the gait pattern in order to delay disease progression. While some strategies had an effect on reducing the EKAM peak (Mündermann et al., 2008; Simic et al., 2012; Gerbrands et al., 2014), it could also be observed that walking speed reduced significantly when a strategy was applied (Gerbrands et al., 2014). Consequently the conclusion could be drawn that OA is still enhanced by the prolonged period of loading the knee. Research shows that a decrease in gait speed can also be seen in OA patients (Mündermann et al., 2005; Huang et al., 2008). People with knee OA walk significantly slower than asymptomatic people and also patients with more severe forms of OA still walk more slowly than people with milder degeneration of knee cartilage (Hunt et al., 2010; Linley et al., 2010).

Contrary to what could be expected, the EKAM peak does not change significantly with different walking speeds (Hollmann, 2014). Also Zeni and Higginson (2009) reported differences in a lot of gait variables when walking faster, except for the EKAM which remained the same for any speeds. But still most researchers correct their EKAM outcomes for this parameter (Gerbrands et al., 2014). The GRF, however, increases linearly with increasing speed (Keller et al., 1996). As the EKAM is highly dependent on the GRF magnitude, it should be expected that the EKAM increases as the GRF increases. Since this is not the case (Zeni and Higginson, 2009; Hollmann, 2014), there have to be factors decreasing the length of the moment arm while walking faster or increasing it when walking slower. Currently, the mechanism that is responsible for changing the moment arm and keeping the EKAM constant regardless gait speed is unknown.

Since the GRF vector is aimed at the body's center of mass (COM), a shift of the COM in the frontal plane would increase or decrease the vector's distance to the center of the knee and thereby change the length of the moment arm. In research, a horizontal displacement of the COM while walking is described by the use of pelvic list (Lin et al., 2014) and lateral pelvic shift towards the weight-bearing limb (Saunders et al., 1952). With faster walking however, the medio-lateral COM displacement is said to be decreasing (Orendurff et al., 2004). Additionally, with the subjects walking more slowly, the medio-lateral pelvic displacement (mlPD) was larger (Orendurff et al., 2004; Swinnen et al., 2013). As this indicates a negative correlation between mlPD and speed, it can be hypothesized that this shift of the pelvis during walking could be the reason for the steady EKAM at all speeds.

Fully understanding the mechanism that is responsible for changing the moment arm would conclusively determine whether corrections for speed are appropriate. Furthermore, it would also provide physiotherapists another variable regarding preventive measures and gait retraining of OA patients in daily practice. Additionally, it might justify whether OA patients should aim at maintaining their usual walking speed instead of reducing it in daily life. Therefore the objective of this study is firstly, to find out the correlation between mlPD and walking speed. Secondly, it has to be verified whether the EKAM also remains constant at different walking speeds for this subject group. Thirdly, if indicated, the changes of the GRF magnitude and mlPD magnitude have to be compared in order to find out whether the mlPD is the reason that the EKAM stays constant at all times.

The findings about the adjustment of the COM lead to the following research question: Is the mlPD the prime determinant of the mechanism that keeps the EKAM constant at all walking speeds in non-arthritic subjects? As the moment arm and walking speed are negatively correlated, it is hypothesized that the mlPD is the prime determinant in altering the length of the moment arm such that it is inversely related to the change of the GRF magnitude with speed.

Methods

Participants

This experimental study included subjects that understood English, German or Dutch and were mentally and physically able to participate. Participation was completely voluntary, but subjects that had been diagnosed with OA of the lower limbs were excluded. Furthermore the exclusion criteria were (previous) injuries to the lower limbs, upper limbs or spine region that altered or impaired gait as well as having an impaired gait pattern for any other reason. Subjects with artificial joints of the lower limbs or any kind of cardiovascular disease were also excluded. Subjects were recruited between October 12th, 2014 and October 29th, 2014 by email (Appendix I) and oral promotion to the staff of Fontys University of Applied Sciences, the students' sports center of the Technical University of Eindhoven as well as to the researchers' circle of family and acquaintances. In order to ensure a sufficiently large sample size to find significance of a correlation, the minimum number of subjects was set at 15.

The study does not involve any risks for the participants, consequently it is a non-WMO obligated study. This is approved by the Máxima Medisch Centrum Veldhoven.

Measurement Tools

The measurements took place in the gait lab of Fontys University of Applied Sciences, Eindhoven, which holds a 14 m long walkway. The utilized hardware was a 3D-gait analysis system from Codamotion, CX1 (Charnwood Dynamics, Ltd.) with a data collection rate of 200Hz. Furthermore a force plate, AMTI OR6-7 (Advanced Mechanical Technology Inc.) with a data collection rate of 1000Hz, was used. The software consisted of a recording program by Codamotion Analysis (Charnwood Dynamics, Ltd.), Visual3D (C-Motion) for the data analysis and SPSS (Statistical Program for Social Sciences; SPSS Inc., v.20) for the statistical analysis.

Both the 3D-gait analysis, which works with the help of infrared markers and cameras, as well as the force plate measurement tool are prevalently used instruments in research. Each of those measurement tools can be seen as golden standards for measuring the EKAM and GRF and many researchers have made use of it (Keller et al., 1996; Miyazaki et al., 2002; Heiden et al., 2009; Bennell et al., 2011; Kean et al., 2012). Additionally, a self-composed questionnaire (Appendix II) was used to confirm that the inclusion and exclusion criteria were met.

Procedure of Measurement

First of all, the included subjects were informed about the testing procedure and possible risks both orally and by an information letter (Appendix III) which also explained the use as well as the storage of the personal data. Then the participants signed an informed consent form (Appendix IV), filled out the questionnaire and changed to short and tight fitting clothes so that there was no interference with the visibility and fixation of the markers. The participant's weight and height, length of the upper and lower leg, as well as the width of the pelvis and the knee were measured, so that joint centers could be determined later on. Then the infrared markers were placed on the subject at eleven different places according to Fig. 1 (Appendix V). Table 1 (Appendix VI) gives an overview of the tasks that needed to be fulfilled by the researcher and the subject. Table 2 (Appendix VI) presents the general outline of the measurement protocol. The subjects first walked up and down the walkway a few times until they stated to be adjusted to the markers. Then, after the static measurement, the subjects were asked to walk barefoot at different speeds, starting from comfortable walking speed, then the fastest to the slowest walking speed as instructed by the researcher. The average speed of each trial was immediately measured by the Codamotion Analysis program. It was defined during the time at which the body's COM was moving throughout the period in which the subject was in view of the camera and stepped on the force plate. Regarding the speed measured, the researchers verbally instructed the participants to walk "a little faster" or "a little slower". It was assumed that a minimum of ten measurements for each subject would be needed when the whole range of speeds, from 0.6 m/s to 1.8 m/s, was divided into equal intervals. This way a wide variety of walking speeds could be covered by each subject. As this requirement generally cannot be met in practice, the maximal acceptable gap between walking speeds not covered was set at 0.24 m/s. This was estimated from defining the minimum speed at 0.6 m/s and the maximum speed at 1.8 m/s, which was in close accordance with speeds used by other researchers (Orendurff et al., 2004; Keller et al., 1996; Zhao et al., 2007). The difference between the speeds was then divided by ten, since this was set as the minimum of amounts to be recorded. Consequently, a maximum gap of twice 0.12 m/s was accepted during the measurements. The actual speed the subjects walked exceeded the expected range of velocities, but the researchers adhered to the maximum gap that was calculated beforehand. To monitor the speeds covered and to ensure no gaps in the measurements, Microsoft Excel was used. By entering the speeds immediately during the testing into a prepared table, the gap magnitudes were automatically checked. Therefore the subjects could be instructed to walk slower or faster in order to cover missing speeds. All measurements were included in the analysis as long as the subjects stepped correctly, meaning with only the whole right foot, onto the force plate. Also measurements with the same mean speeds were taken into the data collection. The measurements were completed with a second static measurement in order to adapt the positioning of the markers in the Visual3D program afterwards in case they fell off and had to be replaced.

Data Analysis

In Visual3D, a standard model (Davis et al., 1991) was applied to the kinematic and kinetic data collected by Codamotion Analysis and was used in order to define segments, joint centers and axes relevant for the measurements (ankle, knee, hip, pelvis). A threshold of 10N on the force plate's vertical axis determined the stance phase. The medio-lateral displacement of the pelvis was calculated relative to the foot placement during the stance phase. It was the largest medio-lateral difference between the maximum and the minimum distance between the projections of the center of the pelvis and the center of the ankle. For the secondary outcome measures, the EKAM was calculated by inverse dynamics.

Statistical Analysis

Pearson correlation coefficients were calculated to investigate the correlation between GRF and speed as well as mlPD and speed using Statistical Package for the Social Sciences v.20 (SPSS Inc., Chicago, IL). Correlation classifications were chosen according to Mukaka (2012): Correlations above 0.9 or below -0.9 were considered to be very high and between 0.7 and 0.9 or -0.7 and -0.9 were interpreted as high. Results above 0.5 or below -0.5 meant that there was a moderate correlation present. Low correlations were set between 0.3 and 0.5 and -0.3 and -0.5. If at least moderate, significant correlations were found, simple linear regression models were applied in order to find the strength of the correlation for mlPD and speed as well as for GRF and speed, respectively. In case no significant moderate correlations were found, the subjects were grouped according to the value of their correlation between mlPD and speed. With the anticipation that certain characteristics might be identified, conclusions could be drawn about when people show which kind of correlation. Here subjects with a low correlation or higher were divided regarding their positive or negative correlation and subjects showing no correlation formed a group of their own.

Results

In total 19 participants were included in the experiment of whom five were female and 14 were male. Their mean age was 40 years (SD = 13 years). Table 3 gives an overview of the descriptive data of the subjects.

Table 3: Descriptive data rounded to 2 decimals

	MEAN	SD
Body weight (kg)	73.43	10.56
Body height (m)	1.77	0.10
Upper leg (m)	0.42	0.05
Lower leg (m)	0.43	0.04
Pelvis width (m)	0.28	0.03
Knee width (m)	0.10	0.01

Considering all measurements of all subjects, the walked mean speed was 1.5 m/s (SD = 0.4 m/s). The fastest speed was 2.81 m/s and the slowest 0.73 m/s. No correlation and no significance could be found between mlPD and speed ($r = 0.006$, $p = 0.921$; Fig. 2). Regarding the secondary outcome measures, the GRF showed a moderate, positive and significant correlation with speed ($r = 0.516$, $p < 0.001$; Fig. 3) and the EKAM peak presented a low and also significant correlation with speed ($r = 0.329$, $p < 0.001$). In the analysis of the EKAM and speed one subject was excluded due to missing data of knee markers.

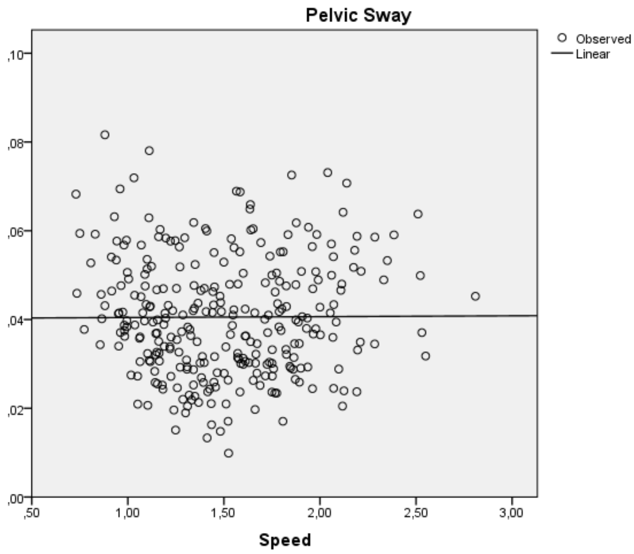

Fig. 2: Scatter plot and estimated curve of correlation between speed (m/s) and mlPD (m)

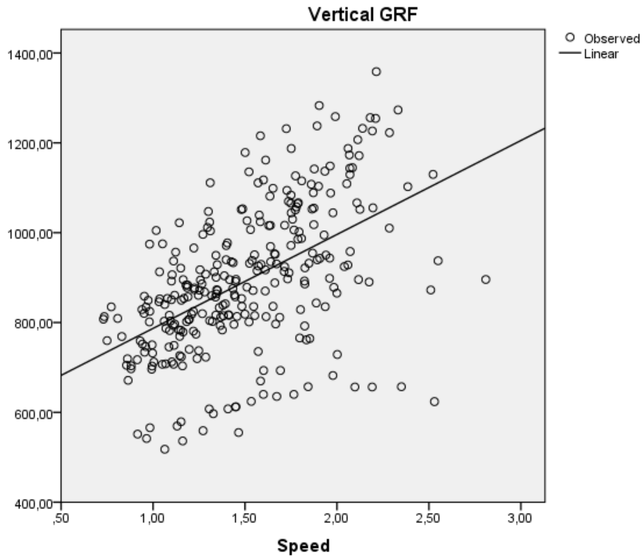

Fig. 3: Scatter plot and estimated curve of correlation between speed (m/s) and GRF (N)

The subgroup analysis resulted in three groups that could be defined regarding the respective correlation between mlPD and speed of each subject. The data of the statistical analysis of the groups is summarized in Table 4.

Table 4: Statistical data of correlation groups

	1) Negative correlation (n = 6)	2) No correlation (n = 7)	3) Positive correlation (n = 6)
GRF – speed	0.697 (p < 0.001)	0.696 (p < 0.001)	0.486 (p < 0.001)
EKAM peak – speed	0.198 (p = 0.068)	0.181 (p = 0.089)*	0.341 (p = 0.001)
mlPD – speed	-0.5 (p < 0.001)	0.034 (p = 0.724)	0.317 (p = 0.002)

*One subject excluded due to missing data of knee markers

Table 5 (Appendix VII) shows the means of the descriptive data of the groups with all measurements from all corresponding subjects included. All groups showed the same average amount of pelvic sway with the whole range of speeds taken into account (0.04 m, SD = 0.01 m). The average EKAM of the first group was 26.5 Nm (SD = 14.6 Nm), with a mean GRF of 889.6 N (SD = 141.8 N). The second group showed a mean EKAM of 29.91 Nm (SD = 13.93 Nm), here one subject had to be excluded due to missing data of knee markers. This group had a mean GRF of 933.59 N (142.16 N). The third group, which included subjects showing a positive correlation, presented a mean EKAM of 40.7 Nm (SD = 15.9 Nm) and a mean GRF of 845.8 N (SD = 190.3 N). While the first and the second group walked 1.42 m/s (SD = 0.36 m/s, range 0.75 m/s to 2.21 m/s) and 1.43 m/s (SD = 0.38 m/s, range 0.73 m/s to 2.39 m/s), the third group walked 1.66 m/s (SD = 0.43 m/s, range 0.92 m/s to 2.81 m/s) on average.

Discussion

The aim of this study was to find out whether the mlPD is the prime determinant of the mechanism that keeps the EKAM constant at all walking speeds. From previous research (Orendurff et al., 2004; Swinnen et al., 2013) it could be hypothesized that the relation of mlPD and speed is inversely related to the change of the GRF magnitude with speed and therefore changes the moment arm accordingly. The results of this study do not confirm this hypothesis in a way that no statistically significant correlation could be found between mlPD and speed.

Since the outcome was not statistically significant, the correlations of each subject were analysed. As approximately a third of the population showed a negative correlation between mlPD and speed, it can be suggested that in this certain group of people the mlPD might be effective in changing the length of the moment arm so that the EKAM stays constant independent of gait speed. Although the first group had a higher GRF on average, the mean as well as the minimum and maximum EKAM were lower compared to the third group. So it seems that the mlPD might be one effective factor, because the first group showed a lower correlation between EKAM peak and speed than the third group.

Also the third group's weak correlation between EKAM and speed might suggest that firstly, increasing the moment arm with increasing speed (and decreasing it with decreasing speed) could be responsible for the fact that there is a correlation present. Secondly, it might mean that other factors may not be as effective in reversing this relation.

Moreover, all groups showed the same average amount of pelvic sway but the way it was adapted to speed was different. While some may have used the mlPD as a factor to alter the length of the moment arm in order to keep the EKAM constant, it can be proposed that the remaining subjects might have made use of other factors, or a combination of factors, in order to achieve this. It was observed that the subjects' weight, body height and sizes of the upper and lower leg as well as the pelvic width of the third group were all lower compared to the other two groups. Due to the decreased body mass that has to be moved, the need to reduce the load on the knee might be less and therefore the demand to keep the EKAM constant might be diminished. This suggests that anatomical characteristics could have an influence on how much or whether the EKAM is kept stable.

Besides, a striking difference between the groups is the speed of walking when looking at the mean speeds of all subjects' measurements. While the first and the second group walked almost with the same speed on average, the third group walked noticeably faster. As discussed in literature (Orendurff et al., 2014), it might be possible that the COM displacement effectively happens during gait at certain velocities, but might become less efficient at the extremes of speeds. Therefore it could be concluded that this might be a reason for the positive relation between mlPD and speed in the third group.

More research on the effectiveness of the lateral pelvic sway in keeping the EKAM stable and on the circumstances during which it might be effective is needed.

Swinnen et al. (2013) and Orendurff et al. (2014) found a negative correlation between mlPD and speed which stands in contrast to the findings of this study. Reasons for that could be that Swinnen et al. (2013) used a motorized treadmill in their study, which might have resulted in a different gait pattern (Alton et al., 1998). Hip adduction, which relatively can be counted as pelvic sway, is 1.41 degrees (SD = 0.96

degrees) less on average during comfortable overground walking compared to treadmill walking (Riley et al., 2007). Although Nymark et al. (2005) and Riley et al. (2007) state only minimal differences in general between overground and treadmill walking, it is questionable whether one can also act on this assumption regarding unknown kinematical relationships. Furthermore Swinnen et al. (2013) did not execute a correlation analysis, but the outcomes of the different velocities were compared to a fixed comfortable walking speed of approximated 1.4 m/s. This pace also formed the maximum speed covered in this study, meaning that the participants only walked slower and at that speed, but not faster. Consequently the question remains whether a statistical significant correlation would have been found at all and if additionally faster velocities were measured.

A striking difference between the current study and the one executed by Swinnen et al. (2013) is the COM placement. In this experiment it is the center of the pelvis, whereas Swinnen et al. (2013) have chosen to focus more on the upper body and therefore placed it closer to the thoracic spine. This of course could result in different outcome as sway of the upper body happens simultaneously during normal gait (Won Lee et al., 2014). Won Lee et al. (2014) stated that with slower and faster walking the trunk sway increases compared to comfortable walking, which could explain the different results between the current study and Swinnen et al. (2013).

Regarding the experiment by Orendurff et al. (2014), one can see that only ten subjects were tested whose correlations between mlPD and speed were not statistically analysed. Although no correlation between mlPD and speed was found in the current study compared to the study by Orendurff et al. (2014), approximately the same average amount of mlPD was found, which was calculated by taking the mean of all measurements and of all subjects. Orendurff et al. (2014) report an overall mean pelvic sway of 3.85 cm (± 1.41 cm SD) at 1.6 m/s, whereupon the present subject group showed a mean pelvic displacement of 4.04 cm (± 1.31 cm SD) at 1.5 m/s. A maximum sway of averaged 6.99 cm (± 1.34 cm SD) at 0.7 m/s and a mean minimum sway of 3.29 cm (± 1.29 cm SD) at 1.61 m/s (SD = 0.22 m/s) was presented by Orendurff et al. (2014), while a comparable amount of maximum 8 cm was found in the current experiment. Although the pelvic sway could not statistically be correlated to speed, this study's population walked a similar minimum speed of 0.73 m/s. However, the minimum amount of pelvic sway measured in the present study was as low as 1cm. This occurrence could be explained by the higher speeds that were covered in the current experiment. While the subject groups of the referenced studies covered a speed range from 0.28 m/s to 1.39 m/s (Swinnen et al., 2013) and from 0.7 m/s to 1.6 m/s (Orendurff et al., 2014), this study's subjects walked between 0.73 m/s up to 2.81 m/s. As mentioned earlier, the gait speed might have an influence on how effectively joint kinematics can affect the COM displacement (Orendurff et al., 2014). Nymark et al. (2005) described substantial differences at extremely slow walking speeds, but there is still a lack of information about consequences of walking at maximum pace in research. It can be proposed that next to a change in the effect of joint kinematics, automatisms can be lost when walking at the extremes of speeds. Therefore, walking between comfortable and maximum gait speed might be one of the reasons for not finding a significant correlation between mlPD and speed.

Furthermore, age could be a determining factor influencing a possible correlation. Since radiographic knee OA can be seen already in most middle aged people (Van Saase et al., 1989), the tibiofemoral angle changes towards a varus position over the years due to the increased loading of the medial compartment of the knee. Almost half of the current population were older than 35 years, meaning that a development

to varus knees could have been existent already. However, the initial position of the knees, which is dependent on the individual, influences the degree of modification of the tibiofemoral angle. The reason for that is the decreased loading of the medial compartment in valgus knees compared to knees in a varus position. As Saunders et al. (1953) described, the natural valgus position of the knees prevents extreme mlPD during walking. So the change of the tibiofemoral angle due to age might have altered the amounts of mlPD used by the participants and partly explain the findings of the present study. Hence this angle could also affect other factors that alter the moment arm of the EKAM as well. As seen in research (Ihlen et al., 2012; Terrier and Reynard, 2014) and discussed by Swinnen et al. (2013), people below the age of 60 years already show altered balance and changes in the gait pattern. In the last-mentioned study the researchers tested two age groups, the younger ranging from 20 to 30 years and the older from 50 to 60 years. The older age group showed significant larger mlPDs than the younger group, suggesting that factors that might alter the moment arm also change with age. Compared to the current study, Orendurff et al. (2014) analysed younger subjects, between 20 and 45 years of age, which could explain the difference in outcome as described above. Moreover, active structures like muscles contribute to joint stability and show increased activation in OA patients (Heiden et al., 2009). Therefore, a tendency for a raised co-contraction of muscles, with the effect that more pressure acts on the knee, could exist in older people as well and impede counteractive mechanisms. This co-contraction of the upper leg muscles might lead to decreased range of motion in corresponding joints due to shortening. Since some of these muscles attach to the pelvis, the mlPD could be influenced as well. Consequently it could be proposed that next to other reasons, age might be a factor influencing mlPD and its effects.
Since the knowledge about the mechanism of why the EKAM stays constant regardless gait speed is very limited, one can think of more explanations for not finding a correlation between mlPD and speed. Here possible factors influencing the moment arm have to be mentioned, since the non-significant result of this study suggest that there must be diverse mechanisms which are used to a different extend between individuals. Other strategies might be for example muscle strength and coordination or certain mechanisms in the ankle and hip while walking. It is likely that one factor, like the mlPD, cannot be generalized to everyone because every person has his or her own individual anatomical preconditions. Although these do not change with gait speed, they might play a crucial role in determining which mechanism is beneficial to apply. Another possibility might be that gait speed influences certain features in such a way that they come into play only under certain speeds. Anatomical differences to be considered next to the valgus or varus position of the knees are for example gender differences which affect the gait pattern or differences regarding joint stiffness and hormonal states. Additionally, the lengths of the upper and lower leg or its ratio as well as leg length asymmetry might be factors changing the initial situation of the individual and determine which mechanism is applied. Being overweight or obese might be determinants to bear in mind as well, apart from many other possible factors.
Further research is needed in order to find out how much influence anatomical differences have on the EKAM, its factors and especially on its relation to speed.

The GRF showed a moderate, positive and significant correlation with speed, as other researchers have found as well (Keller et al., 1996; Hollmann, 2014). There was a low and significant correlation between EKAM peak and speed and therefore this outcome contradicts previous findings (Zeni and Higginson, 2009; Hollmann, 2014), which showed no correlation between those parameters. As the group that

included subjects with a positive correlation between mlPD and speed also showed a low correlation between EKAM and speed, it is likely that this group has influenced the main outcome for EKAM and speed in such a way that it is weakly correlated. A reason for that could be the influence of speed, since this third group walked the fastest on average and had the highest maximum speed, 2.81 m/s. The subjects of the study by Zeni and Higginson (2009) on the other hand walked maximally 2.2 m/s and the ones of Hollmann (2014) had a maximum mean pace of 1.54 m/s. This suggests that walking closer to maximum speed could provoke a correlation between EKAM and speed.
Furthermore, in Hollmann's study (2014) the speed was controlled by a metronome which could have influenced the gait pattern in terms of step length and thereby also the correlation between EKAM and speed could have been affected.
More reasons possibly explaining the differences in the studies could be that on the one hand Zeni and Higginson (2009) did not execute a correlation analysis but checked for significant differences between different walking speeds, groups and other factors. On the other hand, although the correlation that was found was not statistically significant, Hollmann (2014) did not conduct a subgroup analysis which could have revealed correlations between EKAM and speed in some test subjects.
The age range of the subjects in all three studies was also different, since the subjects of the current study were between 23 and 62, the ones of Zeni and Higginson (2009) between 40 and 85 and Hollmann (2014) tested subjects with an average age of 23.75 years (SD = 2.65 years; no range reported). This could maybe have influenced the correlations that were found as well, as it is still a question whether the EKAM also always stays stable in older subjects. Zeni and Higginson (2009) found that most of the times the EKAM does not significantly change with speed between subject groups (control, moderate and severe OA), except when the severe OA group walked at 1.03 m/s (SD = 0.26 m/s) and 1.0 m/s. This suggests that there might be situations or conditions when the EKAM could be weakly related to speed, so more research is needed to clarify this. Also these conclusions can lead to the assumption that there would be no need for researching the correlation between mlPD and speed anymore, as the EKAM might in fact be related to speed. However, the abovementioned reasons for this study's results of the weak correlation between EKAM and speed also propose that this might only be the case under certain circumstances. Consequently there might still be mechanisms, like probably the mlPD, that keep the EKAM constant as long as certain conditions are present. This is still worth researching as these factors can be used for treatment of OA patients and as part of prevention if understood and applied accordingly.

The results suggest that there are kinematic factors changing the length of the moment arm as predicted. It can be proposed that after more research is done, adapting the mlPD in a way that it increases with decreasing speed and the other way around could be used as a treatment method for certain OA patients or as a preventive measure in order to reduce knee load. It could be introduced or improved as a mechanism that alters the moment arm, dependent on the patients' anatomical preconditions. Besides, as the EKAM peak is probably higher in older age, it can be proposed that walking faster while adapting the mlPD accordingly would reduce the EKAM impulse considerably.
Although there are factors, like possibly the mlPD, that keep the EKAM constant at most walking speeds, it seems that this applies only to velocities below and around comfortable walking speed and more research has to clarify the effects of walking close to maximum speed. Therefore, the results suggest that it is indeed necessary for researchers to adapt their outcome for speed until the mechanism of why the

EKAM stays constant is fully understood.

There is no consensus about the cut-off points of correlations in research, consequently the interpretation of the outcome depends on the researcher. The correlation classification commonly used in biomechanical research sets the cut-off point at 0.5 and -0.5, consequently the outcomes above and below these thresholds are interpreted as at least moderate (Vincent, 2005). Although the correlation between GRF and speed is not strong (Keller et al., 1996) the linear relation between those parameters is accepted as a fact in research. Relative to this correlation, the results of the present study which are below 0.5 or above -0.5 can then be interpreted as existing correlations as well. The cut-off point of 0.1 (-0.1), as generally seen in statistics, was considered to be too low with regard to the classification of Vincent (2005). Therefore, in addition to to the physiotherapeutic connection of this topic, it was decided to apply the classification defined by Mukaka (2012) for medical research in this study.

There are certain limitations to this study that have to be mentioned. The sample size regarding the subgroup analysis was quite small, with six to seven subjects per group. Therefore conclusions drawn from this analysis need to be seen as possible and theoretical explanations of what was found. These conclusions however could be used as ideas for future research.
Moreover, the whole subject group was quite heterogeneous considering the age and gender distribution. Nevertheless the different age range that was used in this study compared to related literature increases the generalizability of the data and provides new insight into gaps in research. The fact that only five women took part in the project was not obviously reflected in the results as these subjects were evenly distributed among the groups after analysing the individual subjects.
Another limitation is that the subjects walked barefoot during the experiment, because in daily life barefoot walking is not done frequently. However, this also prevented possible distinctions in outcome, since walking in different shoes would have had an even bigger effect on the walking pattern and kinematics. Additionally, this way the markers could be placed as accurate as possible which was done by one person only. That way they were always placed in the same manner and mistakes were reduced as much as possible.
As a final limitation, one exclusion criteria has to be mentioned. Excluding people with an altered walking pattern does not exclude subjects that have had operations or injuries of the knees. This might have consequences on the kinematics while walking. Although, only two subjects reported having undergone surgery which was more than 15 years ago. These surgeries comprised a meniscal tear repair in the one case and an anterior cruciate ligament as well as a lateral collateral ligament reconstruction in the other case. So all structures were repaired and with the presence of a normal walking pattern it can be expected that the kinematics have been normalized again.

Future research should be conducted on how determining anatomical differences in individuals are related to the factors that influence the EKAM and/or its relation to speed. Additionally, other factors than the mlPD that keep the EKAM constant should be searched for and investigated in such a way that it becomes clear why certain mechanisms work in certain people. Furthermore, it is necessary to find out whether there are indeed circumstances that reveal a correlation between EKAM and speed, for example maximal walking speed.

Conclusion

The mlPD is not the prime determinant of the mechanism that keeps the EKAM constant, but it might be a strategy certain people effectively use. Future research has to find out under which circumstances the mlPD is applied in order to keep the EKAM constant as well as when and which other mechanisms are used. Additionally, the influence of anatomical preconditions on which strategy is effective should be researched. It can be suggested that after clarifying these factors, adapting the mlPD accordingly could be used as a treatment method for certain OA patients or as a preventive measure in order to reduce knee load. Furthermore, the results of this study suggest that certain conditions like maximal gait speed might provoke a correlation between EKAM and speed which has to be clarified by future research.

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Appendices

Appendix I

Email to Subjects

Dear Madam or Sir,

As a 4th year student of the physiotherapy program of Fontys University of Applied Sciences (Eindhoven), I will do a graduation project which includes an experiment about walking and load distributions.
The research will be done in the gait lab of our school and by participating, you not only help that this project can be completed, but also get insight into research done in the field of physiotherapy.

There are no risks involved in this experiment, all is needed are two hours of your time. The testing will be done from October 13th until October 31st, 2014 and I will do my best to plan it as flexible as possible so you can participate.

Please read the information letter in the attachment and the short questionnaire in case you are interested. The questionnaire will be filled in prior to the testing
Let me know before October, 10th whether you like to participate.

I would be very happy to hear from you and welcome you in my study!
If you have any questions, please feel free to contact me any time.

Kind regards,

Stella Veith

Appendix II

Questionnaire Participants

Please fill in the questionnaire veritably and also twice (one for the researcher, one for yourself).

Name: ______________________________

Date of birth: ______________________________

Gender: ______________________________

Weight: ______________________________

Height: ______________________________

Do you suffer from any (previous) injuries that could possibly change the way you walk?
If yes, what? ______________________________

Have you been diagnosed with osteoarthritis?
If yes, where? ______________________________

Do you take any medication?
If yes, what? ______________________________

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

______________________ ______________________
Place, date Signature

Appendix III

Information Letter

Graduation Project – Pelvic displacement during walking

Dear Madam or Sir,

I would like to invite you to participate in my graduation project, a study about measuring the pelvic displacement and the load on the knee during walking at different velocities.
Please read this letter carefully in order to find out whether you would like to participate. If any questions are left, feel free to contact me. My contact details can be found at the end of this letter.

What is this project about?

Osteoarthritis (OA), or the degeneration of one or more joints in the body, is a very common problem in our society and the knee joint is the most affected one. Treatment options so far include physiotherapy, medication and surgery. At the moment, research is done about changing the way OA patients walk in order to alter the load put on the knee and thereby slowing down the degeneration of the joint.
My research aims at finding out whether the displacement of the pelvis during walking at different speeds has a relation to the load put on the knee.
The outcome of this study could have an impact on the physiotherapist's daily work in training the walking patterns of patients with osteoarthritis.

What are we going to do?

First of all, we will measure your body height, weight, upper and lower leg length as well as pelvic and knee width. Then you will be wired with 11 markers mainly on your lower limbs and thorax, therefore it is necessary to wear short and tight sports clothes in order for the infrared cameras to see the markers.
Finally, after initial static measurements you will walk barefoot through the gait lab a couple of times at different speeds.
In total, this will take approximately one hour of your time.

Are you a possible participant?

If you are over the age of 30 and generally healthy, you are very welcome to participate.
However, since we need to make sure there are as little factors as possible influencing the outcome measurements, there are some exclusion criteria.
These are:

- any (previous) injuries that change or have changed your walking pattern
- osteoarthritis in the lower limbs
- cardiovascular diseases

If you are unsure about whether you can participate or not, please contact me and I will answer your questions.

Are there any potential risks?

There are no risks connected to this study.
You will walk in a controlled environment at normal walking speeds (no running or jogging) with a researcher and supervisor present at all times.
Furthermore, you can withdraw your participation at any time without stating any reason. Your participation is entirely voluntary, also after the testing you can still decide to step back and your data will be deleted.

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, but only the researcher and supervisor of this project have the full access to your data.

I would be very glad to hear from you and welcome you to my research project! It would not only be very helpful for me, because without participants conducting this study would not be possible, but I think that it can also be very interesting for you to experience.
So in case this letter did not answer all your questions, please feel free to contact me. If you want to contact the supervisor of this research project or the coordinator of all graduation projects, you can find their contact details below.

I hope to hear from you!

Kind regards,
Stella Veith

- Researcher:
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Appendix IV

Informed Consent

Participation agreement in the study 'Is the medio-lateral pelvic displacement the prime determinant of the mechanism that keeps the EKAM constant at all walking speeds?'

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 describe in the information letter.

I agree to participate in the research.

Name test person:

___________________________ ___________________________

Place, date Signature

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 people concerning this in time.

Stella-Maria Veith (researcher)

___________________________ ___________________________

Place, date Signature

Appendix V

Marker Placement

Infrared markers
1. S.2
2. Left ASIS
3. Right ASIS
4. Cluster marker upper leg (ventral on femur)
5. Medial epicondyle
6. Lateral epicondyle
7. Cluster marker lower leg (dorso-lateral tibia)
8. Base metatarsal V
9. Lateral malleolus
10. Heel
11. Medial malleolus

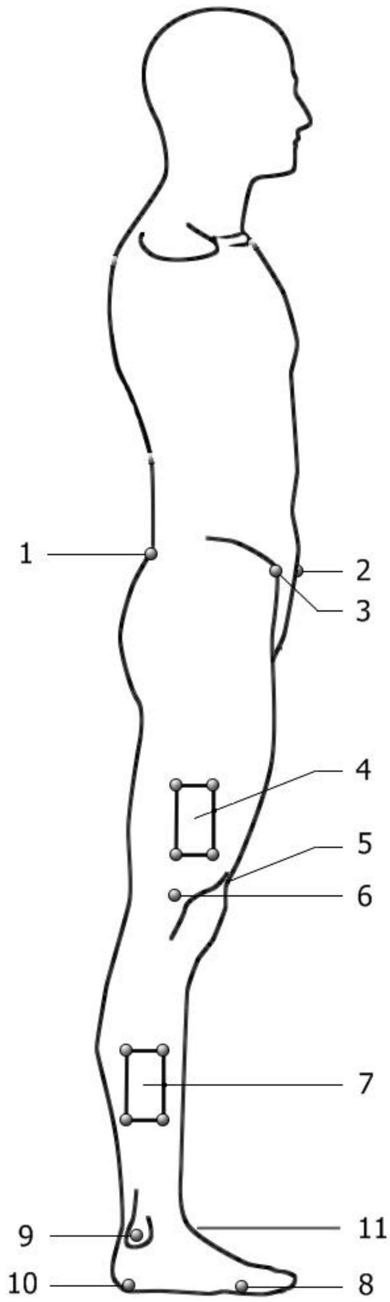

Fig. 1: Protocol 3D
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Appendix VI

Table 1: **Procedure Gait Lab**

NECESSITIES	PREPERATION WITH SUBJECT
1. charge and prepare 3D-marker system with double sided tape	1. Informed Consent needs to be signed
2. Calibration of 3D-system	2. Change to appropriate clothing
3. Calibration of Forceplate	3. Data Sheet needs to be filled in
4. Appropriate (short, tight) clothing available	4. Application of infrared markers according to Protocol 3D (Fig. 1, Appendix V)
5. Informed Consent signed	5. Testing of the marker application and forceplate in a Live View
6. Questionnaire filled in and signed	6. Follow Measurement Protocol
7. Data Sheet filled in	

Table 2: **Measurement Protocol**

TRIAL TYPE	ACTIVITY	TRIAL NAME
Static measurement	- straight standing posture - both feet on the forceplate - hands on shoulders so marker visibility is 100% - record for 8 seconds	Static_pre
Walking conditions	- comfortable walking speed → fastest speed possible → slower than fastest walking speed → slower than comfortable walking speed → slowest speed possible - verbal instructions by researchers - approximately 15 measurements	
TRIAL TYPE	ACTIVITY	TRIAL NAME
Static measurement	- straight standing posture - both feet on the forceplate - hands on shoulders so marker visibility is 100% - record for 8 seconds	Static_post

Appendix VII

Table 5: Descriptive data of correlation groups, rounded to two decimals

		1) Neg. correlation (± SD) *(n=6)*		2) *No correlation (± SD) (n=7)*		3) *Pos. Correlation (± SD) (n=6)*	
Gender:	Male	5		5		4	
	Female	1		2		2	
Age (years)		43	(17)	40	(14)	37	(10)
Weight (kg)		74.1	(5.57)	78.19	(10.23)	67.2	(12.9)
Height (m)		1.80	(0.09)	1.8	(0.09)	1.71	(0.1)
Upper leg (m)		0.44	(0.04)	0.43	(0.04)	0.38	(0.05)
Lower leg (m)		0.45	(0.04)	0.44	(0.04)	0.41	(0.03)
Pelvis Width (m)		0.29	(0.03)	0.29	(0.02)	0.27	(0.02)
Knee Width (m)		0.11	(0.01)	0.10	(0.01)	0.1	(0.01)
Speed (m/s):							
	Average	1.42	(0.36)	1.43	(0.38)	1.66	(0.43)
	Min	0.75		0.73		0.92	
	Max	2.21		2.39		2.81	
GRF (N):							
	Average	889.56	(141.83)	933.59	(142.16)	845.79	(190.33)
	Min	696.17		671.33		517.8	
	Max	1358.51		1273.19		1256.1	
EKAM average (Nm):							
	Average	26.47	(14.6)	29.91	(13.93)*	40.73	(15.91)
	Min	2.35		0.5		17.36	
	Max	54.45		65.31		77.54	
Pelvic sway (m):							
	Average	0.04	(0.01)	0.04	(0.01)	0.04	(0.01)
	Min	0.02		0.01		0.02	
	Max	0.08		0.07		0.07	

*One subject excluded due to missing data of knee markers