# STATISTICAL COMPARISON OF THE KNEE CONTACT FORCES AND KNEE JOINT MOMENTS TO EVALUATE THE LOADING IN THE KNEE WITH FRONTAL PLANE MALALIGNMENT DURING WALKING

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In children and adolescent with valgus malalignment the loading is shifted to the lateral compartment. The aim of this study was to investigate the numerical linear relationship between knee joint moments and medial and lateral knee contact forces in children and adolescents with frontal plane malalignment and typically developed controls. In the 2nd half of stance a significant medium linear relationship was found between the knee adduction moment and the medial and lateral knee contact forces. These results lead to the assumption that the loading in the knee joint in children and adolescent should be analyzed by calculating knee contact forces rather than knee joint moments.

**KEYWORDS:** gait analysis, children and adolescents, musculoskeletal modeling, valgus malalignment.

**INTRODUCTION:** A valgus malalignment is one reason for an increased loading in the lateral compartment and accordingly increases the risk to develop knee osteoarthritis (OA) (Hunter & Wilson, 2009). Therefore, in children and adolescents with frontal plane malalignment, the determination of the knee joint loading separately for the medial and lateral compartment is for special interest. Additionally, an increased valgus angle in the knee joint is identified as an intrinsic risk factor for an anterior cruciate ligament (ACL) injury (Griffin et al., 2000). Furthermore, the number of ACL injuries in children and adolescents increased in the last years (Shaw & Finch, 2017). In comparison to joint moments, joint contact forces not only use the externally applied ground reaction forces, but also internal forces as the muscle forces to calculate the joint loading (Winby et al., 2009). A few studies investigated the relationship between knee joint moments and knee contact forces (KCFs) in elderly people with OA (Kutzner et al., 2013; Meireles et al., 2016). They showed a moderate correlation in the 1st half of stance between the external knee adduction moment (KAM) and the medial knee contact force (mKCF) but not in the 2nd half. Additionally, a stronger relationship in patients with an increased static varus alignment compared to controls was found (Meireles et al., 2016). Nevertheless, they did not investigate the relationship between the KAM and the lateral knee contact force (lKCF).
The aim of this study was to investigate the linear relationship between the knee joint moments and mKCF and lKCF in children and adolescents with and without valgus malalignment. We firstly hypothesized that the relationship between the joint moments and the KCFs is different in the typically developed control group (TD) compared to the patient group. We secondly hypothesized that the relationship between the joint moments and the KFCs is higher in the 1st half of stance compared to the 2nd half of stance.

**METHODS:** Sixteen children and adolescents with valgus malalignment (-5.1° ± 2.0) of the knee (13.0 (11.3 - 13.0) years of age) and 16 sex- and age- matched TD controls (12.0 (12.0 - 12.8) years of age) were gait analyzed (Table 1). Solely patients with a clinical indication for a temporary hemiepiphysiodesis and a pathological valgus alignment of at least one knee according to the mechanical bearing line (deviation was more than 10 mm (Schnurr & König, 2013)) of the lower limb based on a full-length standing anteroposterior radiograph were included (Moreland et al., 1987). All participants and their parents were thoroughly familiarized with the gait analysis protocol. Participants and their

parents gave written informed consent to participate in this study, as approved by the local ethics committee (182/16) and in accordance with the Helsinki Declaration.
Kinematic data were collected barefoot at 200 Hz using an 8-camera motion capture system (MX T10, VICON Motion Systems, Oxford, UK). Ground reaction forces were recorded synchronously at 1000 Hz using two force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) situated at the mid-point of the 15 m long level walkway. To improve the reliability and accuracy when analyzing frontal plane gait data, a lower body protocol (called MA), described in a previous investigation (Stief et al., 2013), was used. Force data were filtered with a fourth order zero-lag low-pass Butterworth filter with a cut-off frequency of 10 Hz. The used model in OpenSim (Lerner et al., 2015) allows predicting mKCF and lKCF separately. The alignment-informed model was adapted and scaled to fit the participant's body weight. Inverse kinematics, static optimization and a joint reaction analysis for calculating the knee contact forces was conducted within OpenSim.
Statistical data analysis was performed with SPSS (version 25, IBM Corporation, New York, NY, USA). For the statistical analyses, the peaks in the 1$^{st}$ and 2$^{nd}$ half of the stance of mKCF were detected. The values of lKCF, KAM and the knee flexion moment (KFM1) in the 1$^{st}$ half and the knee extension moment (KEM2) in the 2$^{nd}$ half were determined at the instant times of the mKCF peaks. The significance level was set at $p < 0.05$. The Shapiro-Wilk test was used to test normal distribution of the analyzed parameters. Differences between patients and TD were tested for significance using an unpaired, two-tailed Student's *t*-test for normal and a Mann-Whitney-*U*-test for non-normal distributed data (Table 1). Linear regression analyses were performed to reveal the relationship between the knee joint moments calculated by the VICON software and the KCFs calculated by OpenSim. We interpreted correlation values below 0.30 as low, between 0.30 and 0.65 as medium, and above 0.65 as high (Cohen, 2013).

**RESULTS:** Normality was confirmed for all variables except for age, lKCF1, KEM2 and KAM2. Differences between groups are summed up in Table 1.

**Table 1: Statistical comparison of the anthropometrics and the knee joint variables.**

| Parameters | | Patients | TD | *p*-values |
|---|---|---|---|---|
| Gender (male/female) | | 12 / 4 | 12 / 4 | - |
| Age [years] | | 13.00 (11.25–13.00) | 12.00 (12.00–12.75) | 0.309 |
| Height [m] | | 1.69 ± 0.09 | 1.57 ± 0.10 | **0.001** |
| Body weight [kg] | | 68.60 ± 12.05 | 44.26 ± 9.02 | **< 0.001** |
| BMI [kg/m$^2$] | | 23.91 ± 3.05 | 17.71 ± 1.96 | **< 0.001** |
| 1$^{st}$ half of stance | mKCF1 [N/(kg x m/s$^2$)] | 1.37 ± 0.29 | 2.00 ± 0.38 | **< 0.001** |
| | lKCF1 [N/(kg x m/s$^2$)] | 0.90 (0.72–1.30) | 0.73 (0.29–1.17) | 0.228 |
| | KFM1 [Nm/(kg x m)] | 4.77 ± 2.11 | 9.20 ± 3.85 | **< 0.001** |
| | KAM1 [Nm/(kg x m)] | 2.18 ± 1.25 | 5.83 ± 1.72 | **< 0.001** |
| 2$^{nd}$ half of stance | mKCF2 [N/(kg x m/s$^2$)] | 1.984 ± 0.341 | 2.37 ± 0.39 | **0.002** |
| | lKCF2 [N/(kg x m/s$^2$)] | 0.93 ± 0.25 | 0.58 ± 0.24 | **< 0.001** |
| | KEM2 [Nm/(kg x m)] | -1.67 (-3.06–-0.62) | -3.84 (-4.86–-2.52) | **0.001** |
| | KAM2 [Nm/(kg x m)] | 1.37 (1.08–2.05) | 3.56 (2.58–4.50) | **< 0.001** |

*Normal distributed data are shown as mean ± standard deviation; not normally distributed data are shown with median (interquartile range); significant differences are **bold** printed. BMI: body mass index; mKCF: medial knee contact force; lKCF: lateral knee contact force; KFM: knee flexion moment; KEM: knee extension moment; KAM: knee adduction moment.*

For the patients group no significant relation was found between mKCF1 and KFM1 or KAM1. In contrast, a significant positive high relation between lKCF1 and KFM1 ($p < 0.001$, $r = 0.738$) was found. Furthermore, significant positive and negative medium relations were found between mKCF2 and KEM2 ($p = 0.023$, $r = -0.389$), mKCF2 and KAM2 ($p = 0.004$, $r = 0.498$), and lKCF2 and KAM2 ($p < 0.029$, $r = -0.370$) (Table 2). For TD, significant medium to high relations were found between lKCF1 and KFM1 ($p$ = 0.001, $r$ = 0.696), mKCF2 and KAM2 ($p$ = 0.043, $r$ = 0.442) and lKCF2 and KAM2 ($p$ = 0.029, $r$ = -0.370) (Table 2).

**Table 2: Linear relationship analysis between the peak of the knee flexion moment (KFM1), knee extension moment (KEM2) and the peaks of knee adduction moment (KAM) and the medial and lateral knee contact forces (mKCF, lKCF) for the patient and TD group.**

| | | Dependent variable | Independent variable | *r* | *p* | *95 % confidence intervals* |
|---|---|---|---|---|---|---|
| Patients | $1^{st}$ half of stance | mKCF1 | KFM1 | 0.120 | 0.275 | -0.040 – 0.073 |
| | | | KAM1 | 0.112 | 0.289 | -0.070 – 0.122 |
| | | lKCF1 | KFM1 | ***0.738*** | ***< 0.001*** | ***0.079 – 0.174*** |
| | | | KAM1 | -0.187 | 0.176 | -0.171 – 0.063 |
| | $2^{nd}$ half of stance | mKCF2 | KEM2 | ***-0.389*** | ***0.023*** | ***-0.200 – -0.002*** |
| | | | KAM2 | ***0.498*** | ***0.004*** | ***0.048 – 0.294*** |
| | | lKCF2 | KEM2 | -0.216 | 0.140 | -0.117 – 0.035 |
| | | | KAM2 | ***-0.370*** | ***0.029*** | ***-0.188 – 0.003*** |
| TD group | $1^{st}$ half of stance | mKCF1 | KFM1 | 0.394 | 0.065 | -0.013 – 0.091 |
| | | | KAM1 | 0.345 | 0.095 | -0.043 – 0.196 |
| | | lKCF1 | KFM1 | **0.696** | **0.001** | **0.041 – 0.158** |
| | | | KAM1 | 0.362 | 0.084 | -0.055 – 0.286 |
| | $2^{nd}$ half of stance | mKCF2 | KEM2 | -0.254 | 0.171 | -0.140 – 0.052 |
| | | | KAM2 | **0.442** | **0.043** | **-0.019 – 0.254** |
| | | lKCF2 | KEM2 | -0.327 | 0.108 | -0.094 – 0.023 |
| | | | KAM2 | **-0.474** | **0.032** | **-0.162 – 0.005** |

**DISCUSSION:** In previous studies the knee joint loading was investigated by the external KAM. In children and adolescents with valgus malalignment, the loading in the lateral compartment is for special interest because the loading is shifted to that compartment. Additionally, the risk to develop an ACL injury is increased with a valgus malalignment. Therefore, we calculated the medial and lateral knee contact forces separately in OpenSim. Furthermore, we investigated the statistical linear relationship of the peaks in the $1^{st}$ and $2^{nd}$ half of stance between the knee joint moments in the sagittal and frontal plane with the mKCF and lKCF.

Our study showed that no significant relationship exists between KAM and mKCF or lKCF in the $1^{st}$ half of stance, neither for the patient nor the TD group. We can conclude that the external KAM therefore is not a good predictor for the medial and lateral knee joint loading. In the $2^{nd}$ half of stance 24.8 % of the variance of mKCF and 13.7 % of the variance of lKCF can be explained by KAM for the patient group. For TD, 19.5 % of mKCF and 22.5 % of lKCF can be explained by the KAM.

Our results are in contrast with Kutzner et al. (2013) and Meireles et al. (2016) who showed a moderate to good positive relationship of KAM with mKCF in the $1^{st}$ half of stance. Furthermore, they showed a less strong positive relationship in the $2^{nd}$ half. Additionally, Meireles et al. (2016) showed an improved prediction of mKCF with a combination of the KFM and the KAM. These differences in our findings could be explained by the different investigated population groups. Kutzner et al. (2013) and Meireles et al. (2016) investigated elderly people with and without OA whereas in our study children and adolescents with and without valgus malalignment were examined. In addition, Kutzner et al. (2013) measured the KCFs by an instrumented prosthesis. It was previously shown that patients with knee prosthesis experience a different gait pattern compared to participants with a natural knee (McClelland et al., 2007). Furthermore, it was shown that patients with OA show a different gait pattern (Mündermann et al., 2005) and muscle activity (Rutherford et al., 2013) compared to people without OA. These differences affect the outcome of the musculoskeletal modelling and could explain the differences in our findings compared to Kutzner et al. (2013) and Meireles et al. (2016).

Further research should focus on the determination of the relationship between moments and contact forces in more dynamic movements. Additionally, up-to-date no other study is known investigating the loading in the knee joint for the lateral compartment separately during a dynamic movement and its effect on ACL injury risk.

**CONCLUSION:** Our study showed that the determination of the external KAM is an insufficient predictor for the internal KCFs in children and adolescent with and without valgus malalignment. Therefore, we suggest to investigate the knee joint loading by calculating the more precise internal KCFs rather than the KAM. Additionally, our study showed that the KAM is not a good predictor of the knee joint loading independently of the leg alignment. Finally, further research is necessary to evaluate the effect of an increased lKCF regarding ACL injury risk.

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