Walking kinematics in subjects with asymptomatic *genu recurvatum*: lower limb joint angles and effect of speed

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Abstract

The aim of this study was to carry out a kinematic analysis of the lower limb during gait in subjects with asymptomatic *genu recurvatum*. The sagittal plane kinematics of the lower limb during gait in a group of 13 subjects with *genu recurvatum* was shown to be significantly different to that of a group of 13 control healthy subjects. An increase in extension and a decrease in flexion of the hip and knee joints as well as an increase in dorsal ankle flexion and a decrease in plantar flexion of ankle joints were observed through the computation of angular ranges of motion. The onset of several kinematic events of the gait cycle was also different in both groups. The results obtained show that subjects with a *genu recurvatum* adopted a significantly different kinematics than healthy subjects, which may be linked to premature wear of the knee articular cartilage.

Keywords: *genu recurvatum*, walk, joint angles, kinematics, speed.

1 Introduction

Genu recurvatum (GR) is defined by a hyperextension of the knee beyond 5° (Loudon 1998); literally, the knee 'bends the other way'. Except in neurological disorders, it is most often bilateral, symmetrical, of constitutional origin and painless, due to ligamentous hyperlaxity (Bussière *et al*. 2001; Demey Lustig, Servien & Neyret 2013). Despite the existence of ligament hyperlaxity, the subjects are considered 'healthy'. The reported proportion of GR is found to be between 10% to 25% (Beighton, 1973; Al-Rawl, Al-Aszawi and Al-Chalabi 1985).

GR may increase valgus and femur internal rotation. Therefore, several structural modifications are associated with GR: an ascent and eccentricity of the patella (the greater the internal rotation of the femur, the more patella becomes lateralized) as well as an accentuation of the varus with a tibial tuberosity more lateral regarding trochlea (Bizot n.d). Having a GR is therefore not without consequences on the knee's articular balance. It changes the pressure distribution on the knee and especially on the anterior part of the tibial plateaus by excessive unwinding of the femoral condyles (Bussière *et al.* 2001). GR may therefore be responsible for premature wear of the articular cartilage and consequently contribute to knee osteoarthitis. The presence of GR in patients undergoing total knee arthroplasty is not uncommon (Seo *et al.* 2017).

The analysis of lower-limb kinematics of subjects presenting an asymptomatic GR during gait, obtained through the study of hip, knee and ankle joint angles in the sagittal plane, has not been addressed in the literature so far. We have compared the latter kinematics to that of control subjects (without GR) to better identify and evaluate the impact of this knee deformity on the gait pattern. Moreover, since lower limb kinematics is influenced by the speed of walk (Mannering, Young, Spelman & Choong 2017), it is reasonable to assume that lower limb kinematics of GR subjects is speed-dependent. We have studied the interplay between GR and speed by asking participants to walk at three different speeds.

2 Material & methods

2.1 Population

An online questionnaire was proposed to the students of the Haute École Louvain en Hainaut (HELHa), Montignies-sur-Sambre site. Subjects were then recruited based on their answers to the questionnaire. Each subject had to be over 18 years and have a Body Mass Index smaller than 30 $kg.m^{-2}$. Participants were not to be pregnant, practising classical dance, gymnastics, or high intensity sports. It was also asked that the participants had no history of trauma to the lower limbs or spine during the 6 months prior to the measurement. Participants with Elhers-Danlos syndrome were excluded. A check of the anterior and posterior cruciate ligament's integrity was performed using Lachman and Drawer tests. A single trained experimenter performed the tests (P.L.). A total of 26 subjects were included in the study and divided according to their maximal passive knee extension into two groups of 13 subjects. The first group included 'control' subjects, i.e. those with knee extension not exceeding 5° of passive hyperextension (age = 21 ± 1 years, weight = 63 ± 11 kg, height = 1.69 ± 0.10 m, passive knee range of motion: -3 ± 1°, 9 women/4 men), the second group included subjects with GR (age = 21 ± 2 years, weight = 65 ± 11 kg, height = 1.68 ± 0.10 m, passive knee range of motion: -12 ± 3°, 9 women/4 men). Negative knee angles denote knee hyperextension. Also note the importance to consider the position of the subject when measuring the knee hyperextension: in supine or standing. In the latter case, values of 10-15° are not uncommon in asymptomatic GR subjects, as observed by Murphey *et al.* (1971).

2.2 Protocol

Measurements were performed while the subjects were walking on a treadmill at 3 speeds: slow (V1 = 2.5 $km.h^{-1}$), medium (natural, V2 = 4.8 $km.h^{-1}$) and fast (V3 = 6.5 $km.h^{-1}$). Kinematic data were collected on 15 consecutive gait cycles (15x2 strides) using a VICON® motion capture system (VICON Motion Systems Ltd., Oxford, UK) composed of 8 opto-electronic cameras and 16 passive markers applied according to the VICON® lower limb Plug-in-Gait model (VICON Motion Systems Ltd, 2017). The markes were placed on anatomical landmarks that can be palpated, i.e., on the anterior and posterior superior iliac spines, on the knee flexion/extension axis, on the lateral malleolus along the imaginary line passing through the transmalleolar axis, on the head of the 2nd metatarsal and on the calcaneus, on the lower third of the lateral aspect of the thigh and the leg. The beginning and end of a given gait cycle was identified as two successive heel strikes of the same foot.

The data provided by the Nexus® software (linked to VICON®) therefore included all the markers positions over time as well as the value of the joint angles of the three main joints of the lower limb in sagittal plane, namely the hip, knee and ankle, during the entire acquisition. R Studio (version 3.4.4.) was used to identify the local extrema of each of the angular curves and to calculate the times at which these extrema occured. The local extrema are the parameters recorded and used in the statistical analysis, see Fig. 1 for typical traces. Note that only the data from the right knee were used.

Statistical analysis of the data from the entire study was performed, using Sigmaplot® v.11.0 software, on the explanatory variables of the study, i.e. subject status (*recurvatum* or control) and walking speed (V1, V2 and V3). The interaction of these two parameters (status × speed) was also tested on all the variables. A two-factor repeated measures ANOVA was therefore applied (significance threshold =

0.05), after checking the homoscedasticity and normality of the distribution of results. A t-test was also performed on the anthropometric data of both groups.

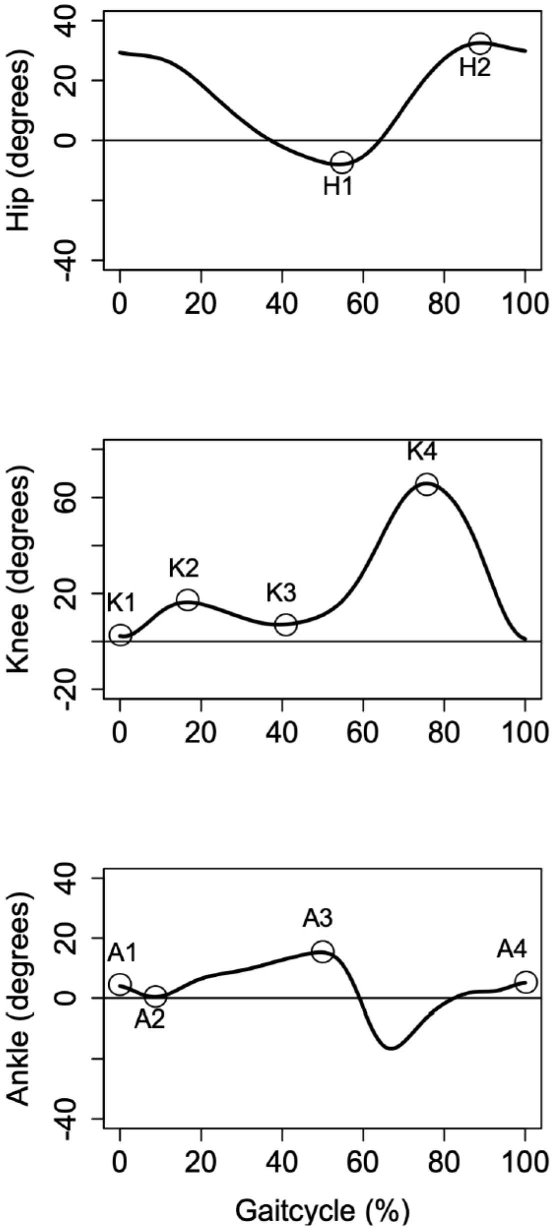

Figure 1: Typical traces of joint angles in sagittal plane versus time, normalized in % of gait cycle (solid lines). Parameters collected are displayed and labelled by a letter+a number (points). They correspond to the local extrema of obtained curves.

3 Results

3.1 Population

Analysis of the anthropometric data (gender, age, height, weight and BMI) and walking speeds of the subjects did not reveal any significant differences between the groups. In the following, we will mostly mention significant differences for the sake of clarity. The interested reader may find a full description of the results in Dierick, Schreiber, Lavallée & Buisseret (2021).

3.2 Impact of genu recurvatum

Typical plots of hip, knee and ankle joint angles in sagittal plane during a gait cycle are shown in Fig. 1, and the full results are presented in Table 1. Subjects with GR have a significantly greater maximum hip extension amplitude (H1) than healthy subjects (p<0.001). This finding is also valid for knee extension during the unipodal support phase (K3). There are significant group effects on maximal knee extension during unipodal stance (K3) during the 3 walking speeds (p=0.002 and p<0.001). The GR subjects all present a knee hyperextension in K3, in contrast to control subjects. Regarding knee joint amplitude during the oscillating phase (K4), the control subjects bend the knee significantly more (p=0.038).

	V1		***V2***		***V3***		***p***		
	GR	***CTRL***	***GR***	***CTRL***	***GR***	***CTRL***	***Status***	***Speed***	***St x Sp***
H1	-13.2 ± 6.3	-8.1 ± 4.0	-18.3 ± 5.7	-13.9 ± 4.4	-20.5 ± 5.0	-15.9 ± 4.5	0.019	<0.001	0.738
H2	25.6 ± 7.1	28.6 ± 4.0	30.5 ± 6.2	32.8 ± 4.4	36.0 ± 7.2	37.6 ± 1.3	0.284	<0.001	0.539
K1	-2.2 ± 5.0	1.3 ± 3.3	-3.0 ± 5.7	-0.8 ± 2.9	-1.8 ± 5.1	0.3 ± 3.5	0.111	0.051	0.437
K2	7.8 ± 3.1	8.9 ± 3.7	13.1 ± 5.2	15.2 ± 2.9	19.0 ± 5.3	20.1 ± 3.3	0.288	<0.001	0.754
K3	-2.8 ± 4.0	1.8 ± 1.9	-4.2 ±4.8	1.8 ± 3.1	-17.7 ± 4.4	0.5 ± 3.0	<0.001	<0.001	0.010
K4	53.5 ± 4.4	54.9 ± 3.6	59.5 ± 5.8	63.1 ± 3.5	59.1 ± 3.6	63.2 ± 2.9	0.038	<0.001	0.123
A1	1.9 ± 3.4	-0.8 ± 3.2	3.1 ± 3.8	-0.2 ± 2.9	3.8 ± 3.8	2.6 ± 3.2	0.065	<0.001	0.062
A2	17.3 ± 2.8	15.8 ± 3.3	15.9 ± 3.7	14.8 ± 2.1	13.5 ± 3.6	12.6 ± 3.0	0.271	<0.001	0.807
A3	-4.8 ± 6.4	-4.8 ± 6.1	-11.9 ± 6.3	-16.2 ± 6.4	-16.8 ± 5.0	-17.6 ± 5.6	0.393	<0.001	0.130
A4	10.3 ± 2.6	6.3 ± 2.7	9.8 ± 2.9	5.1 ± 3.0	12.0 ± 3.1	8.7 ± 3.3	<0.001	<0.001	0.459

Table 1: Measured Hip (H1, H2), Knee (K1, K2, K3, K4) and Ankle (A1, A2, A3, A4) angles, in °, for the control (CTRL) and genu recurvatium (GR) groups. Data are given under the form average ± standard deviation. p-values from the 2 way ANOVA are given in the last three columns. The measured angles are graphically explained in Fig. 1.

	V1		V2		V3		p		
	GR	**CTRL**	**GR**	**CTRL**	**GR**	**CTRL**	**Status**	**Speed**	**St x Sp**
H1	56.6 ± 2.9	55.5 ± 3.3	55.2 ± 2.4	54.0 ± 1.1	53.7 ± 2.1	53.4 ± 1.2	0.212	<0.001	0.710
H2	91.3 ± 4.7	89.9 ± 3.3	93.8 ± 6.9	88.5 ± 1.6	94.8 ± 7.3	91.5 ± 5.7	0.075	0.023	0.120
K1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.000	1.000	1.000
K2	14.7 ± 2.9	14.4 ± 2.9	15.5 ± 1.2	15.6 ± 1.2	16.0 ± 1.6	15.8 ± 1.2	0.780	0.022	0.922
K3	46.3 ± 4.0	43.3 ± 7.8	45.0 ± 2.5	42.7 ± 2.3	44.4 ± 1.7	42.9 ± 2.2	0.058	0.408	0.719
K4	76.1 ± 2.1	75.5 ± 2.5	76.0 ± 1.3	75.5 ± 0.7	75.3 ± 1.1	74.9 ± 1.0	0.350	0.064	0.978
A1	8.3 ± 2.1	5.4 ± 2.9	8.9 ± 1.4	7.4 ± 1.3	8.6 ± 1.5	8.6 ± 1.5	0.005	0.002	0.016
A2	52.7 ± 4.5	51.3 ± 3.2	48.9 ± 6.2	47.6 ± 2.6	36.3 ± 9.6	37.1 ± 7.2	0.781	<0.001	0.687
A3	70.2 ± 1.9	69.4 ± 2.8	67.7 ± 1.8	67.0 ± 1.5	64.8 ± 0.9	64.4 ± 1.3	0.248	<0.001	0.897
A4	87.3 ± 6.9	84.4 ± 3.8	92.0 ± 6.4	95.1 ± 6.0	97.2 ± 3.9	98.1 ± 4.0	0.802	<0.001	0.108

Table 2: Moments at which the events H1, H2, K1, K2, K3, K4, A1, A2, A3, A4, displayed in Fig. 1, occur, for the control (CTRL) and genu recurvatium (GR) groups. Numbers are expressed in % of the gait cycle. Data are given under the form average ± standard deviation. P-values from the 2-way ANOVA are given in the last three columns.

3.3 Impact of speed

The amplitude of hip extension as well as maximum hip flexion (H1 and H2) increased with speed (p<0.001) in both groups. When the foot was placed flat on the ground (K2), the flexion increased in both groups. The same behavior was observed in the maximum knee flexion (K4) during the oscillating phase. There was no influence of speed on knee angulation during the unipodal support phase (K3) for healthy subjects. On the other hand, this extension was significantly increased (p<0.001) in GR subjects during the transition from V1 to V3 and from V2 to V3. There was a significant interaction between groups and treadmill speed for knee extension during unipodal support phase.

Ankle kinematics showed a significantly reduced (p<0.001) dorsal foot flexion amplitude during the unipodal support phase (A2) as speed increased, for both groups. Conversely, plantar flexion was increased during the propulsion phase (A3), i.e. at the time of toe off, for both groups.

The occurrence time of events during the gait cycle, corresponding to the same points discussed for the angular values, was influenced by speed of walking. Results are given in Table 2. The maximum extension of the hip (H2) was significantly earlier (p<0.001) as the speed increases, contrary to its maximum flexion which arrives later (p=0.023). K2, when the foot lied flat on the ground, was significantly increased with the speed of walk (p=0.022). The plantar flexion A3 appeared significantly earlier in healthy subjects when the speed increased from V1 to V2 and from V1 to V3 (p<0.001 and p=0.006). Speed also significantly changed the time of onset of the unipodal support phase event (A2), so that it occured earlier in the cycle. Maximum dorsal flexion preceding heel strike (A4) occured significantly later (p<0.001).

4 Discussion

Parameters extracted from hip, knee and ankle angles are common benchmarks in the kinematic analysis of walking (Kadaba, Ramakrishnan & Wootten 1990; Kirtley 2006; Noyes *et al*. 2016). The set of values as well as their moment of appearance in the gait cycle of the control subjects is comparable to the values presented in the literature for comfort speed on a treadmill (Kirtley 2006; Kadaba *et al.* 1990; Winter 1987), corresponding to V2 in this study. The accuracy reached on the various anatomical landmarks is obsiously a limitation of our study. According to Merriaux (2017), the error associated to the tracking of one anatomical landmark by a VICON system is of order 1mm, including the error due to the placement of the marker by the experimenter. This leads to an error of 0.2° on an angle. Our significant differences between angles are beyond that error, so it is relevant to discuss them. We also point out that the markers were always placed by the same researcher (P.L.) so that the associated error is minimized.

Noyes *et al.* (2016) reported a detailed kinematic analysis of walking with GR and its evolution following a training program. However, the subjects included in their study presented GR following a knee posterolateral ligament complex injury. Even though their sample is different from our GR group, it is not impossible to make a comparison with our results. In both studies the observation of a walking pattern characterized by the punctual appearance of knee hyperextension at two moments of the support phase during the gait cycle (at the heel strike and during the unipodal support phase) can be made. Reducing knee hyperextension during unipodal stance is therefore a relevant goal for a therapist managing a GR patient. This can be done first through static exercises. Raising the toes without holding the knee in *recurvatum* is an exercise that may help normalize the patient's heel strike.

Our study confirms the observations of Kwon *et al.* (2015) and Dziuba *et al.* (2015): hip extension and flexion increase with speed. Concerning the knee extension at heel strike tends to decrease from slow to natural speed and increase from natural to fast speed in all subjects. Mannering *et al*. (2017) report the same decrease.

Noyes *et al.* (2016) showed that knee hyperextension was significantly increased in the GR subjects and that knee flexion during loading on the limb was significantly greater in healthy subjects. We observed this same phenomenon in our study; however the difference was not statistically significant (p=0.288). Finally, we found that knee flexion during the oscillation phase was significantly lower in subjects with GR. Our GR subjects flex their knees less than control ones. As explained by Mannering *et al.* (2017), the increased knee flexion during the support phase of healthy high-speed walking may allow the internal forces of the knee to be distributed over a larger area of the tibiofemoral cartilage. Lelas, Merriman, Riley and Kerrigan (2003) also hypothesize that this knee flexion during the lean phase is necessary to allow better 'shock absorption' during healthy walking. Then, the behaviour of GR subjects could lead to a less efficient absorption during walking and consequently damage their joint earlier than in subjects without deformity.

To the best of our knowledge, it is the first study that characterizes lower limb kinematic changes in asymptomatic individuals with GR compared to individuals without knee deformation and assesses the influence of walking speed. Characterization of kinematic changes during gait in asymptomatic individuals with GR is very important since repeated abnormal movements of the knee could lead to premature degeneration of its anatomical structures. Seo *at al.* (2017) put forward the idea that GR, by affecting the integrity of the joint, could indeed induce premature wear of the articular cartilage and therefore be the cause of knee osteoarthritis. The results of our study confirm the hypothesis that GR influences the kinematics of walking. Subjects with GR flex their knees less, at any speed, than healthy subjects during the two flexing phases of the gait cycle. According to Mannering *et al.* (2017) and Lelas *et al.* (2003), the compressive forces are therefore less well distributed over the knee's articular surfaces during the total flexion/extension amplitude throughout the gait cycle. These phenomena could be responsible for the premature wear of the knee's articular cartilage in subjects with GR.

The identification of GR during walking should allow the physiotherapists to propose relevant exercises such as those presented by Noyes *et al.* (2016). In the latter study, it was shown that after the training program gait patterns of GR normalized. To our knowledge, a similar study has not yet been conducted on asymptomatic GR subjects. Finally, we recall that the assessment of lower limb joint angles at slow, medium, and fast walking speeds is a strong point of the study. Our findings show that walking speed profoundly influences joint angles in the two groups and that assessment of GR at fast speed is required to complete the understanding of the kinematics in this painless population. However, it is preferable to first work at low speed with a GR patient in order to improve his/her awareness of the motor strategy to adopt, and then only increase speed. Note however that we have not computed Beighton's score in our GR group, hence we cannot *a priori* apply our results to patients with global ligamentous hyperlaxity.

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