Journal of Biomechanics 46 (2013) 1408–1412

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Changes in valgus and varus alignment neutralize aberrant frontal plane knee moments in patients with unicompartmental knee osteoarthritis

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ARTICLE INFO

Article history:
Accepted 20 January 2013

Keywords:
Knee angular impulse
Knee moment
Osteoarthritis
Alignment
Osteotomy

ABSTRACT

To elucidate the effects of frontal plane lower limb alignment on gait biomechanics, we compared knee joint moments and frontal plane angular impulse before and after varus or valgus producing osteotomy in patients with lateral or medial compartment osteoarthritis, and in healthy participants with neutral alignment. Thirty-nine subjects participated (13 valgus gonarthrosis, 13 varus gonarthrosis, 13 controls). Patients underwent 3D gait analysis and radiographic assessment of alignment (mechanical axis angle; MAA) before and 6 months after surgery, and were compared to controls. Mean changes (95%CI) in frontal plane angular impulse indicated a 0.82%BW·Ht·s (0.49,1.14) increase in adduction impulse in patients after varus osteotomy, and a 0.61%BW·Ht·s (0.37,0.86) decrease in adduction impulse in patients after valgus osteotomy, equating to a 53% and 45% change from preoperative values, respectively. Preoperative frontal plane angular impulse was significantly different between both patient groups and controls before surgery, but not after. The cross-sectional data suggest that frontal plane angular impulse is very highly correlated to MAA before surgery ($R=0.87$), but not after ($R=0.39$), and that an adduction impulse predominates until 7° of valgus, at which point an abduction impulse predominates. The prospective surgical realignment data indicate that for every 1° change in MAA toward varus, there is a 0.1%BW·Ht·s (or 1.6 N m s) change in frontal plane knee angular impulse toward adduction, and vice versa. These overall findings illustrate the potent effects that lower limb alignment can have on frontal plane gait biomechanics.

1. Introduction

Epidemiological studies suggest frontal plane alignment of the lower limb, quantified as the mechanical axis angle (MAA), plays an important role in the development and progression of knee osteoarthritis (OA), presumably due to its effect on biomechanics (Sharma et al., 2012, 2010). Gait analysis provides insight into how frontal plane alignment contributes to knee joint biomechanics, and how modifications in alignment can affect dynamic joint loads. In neutral alignment, the line of action of the ground reaction force (GRF) during single limb support passes medial to the knee joint center, creating a lever arm in the frontal plane, an external adduction moment about the tibiofemoral joint, and greater loads on the medial compared to lateral compartment (Andriacchi, 1994). In varus gonarthrosis, the knee adduction moment, angular impulse and distribution of load on the medial compartment are higher and more sustained (Landry et al., 2007; Thorp et al., 2006a), with prospective risk factor studies suggesting potent effects on disease progression (Bennell et al., 2011; Miyazaki et al., 2002).

The effect of valgus alignment on knee biomechanics is less clear. Previous studies suggest load distribution shifts from greater medial compartment, to equal, to greater lateral compartment with increasing valgus (Bruns et al., 1993; Harrington, 1983; Johnson et al., 1980). Due to the typical predominance of a knee adduction moment during walking, it is unclear what degree of valgus is required to create an external abduction moment. Indeed, we are aware of limited published 3D gait analyses in patients with lateral compartment OA (Butler et al., 2011; Weidow et al., 2006).

Consistent with being a risk factor for OA, several treatments, both conservative and surgical, aim to change the moments about the knee in attempt to lessen aberrant loads on the more diseased

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http://dx.doi.org/10.1016/j.jbiomech.2013.01.024

compartment (Lutzner et al., 2009; Reeves and Bowling, 2011). Surgical osteotomy provides a model in which to study the effects of changing alignment in patients with knee OA. Various osteotomy procedures can be performed at the proximal tibia and distal femur to correct limb malalignment in both varus and valgus directions (Dowd et al., 2006). To elucidate the effects of frontal plane alignment on gait biomechanics, we evaluated knee joint moments before and after varus or valgus producing osteotomy in patients with lateral or medial compartment OA, and in healthy participants with neutral alignment. Our primary hypothesis was that the knee adduction impulse and peak knee adduction moment would increase in patients after varus osteotomy, and decrease in patients after valgus osteotomy. Further, differences between patients and controls would be observed preoperatively, but not postoperatively. Finally, changes in frontal plane gait mechanics would be explained primarily by changes in MAA.

Table 1
Demographic and clinical characteristics.

Characteristics	Valgus Gonarthrosis group	Varus Gonarthrosis group	Healthy control group
	Mean (SD)	Mean (SD)	Mean (SD)
Age (years)	49 (10)	50 (7)	44 (15)
No. of males	6/13 (46%)	7/13 (53%)	9/13 (69%)
Mass (kg)	91.81 (19.06)	92.21 (16.39)	85.64 (11.68)
Height (m)	1.76 (0.09)	1.73 (0.13)	1.74 (0.07)
BMI (kg/m^2)	29.48 (4.79)	30.85 (4.78)	28.18 (3.19)
Mechanical axis angle (deg.)[a]	6.64 (3.85)	−6.72 (3.92)	−0.19 (0.85)
Kellgren and Lawrence grade[b]			
1	0	0	–
2	5	3	–
3	5	7	–
4	3	3	–

[a] Mechanical axis angle $>0^\circ$ indicates valgus alignment, Mechanical axis angle $<0^\circ$ indicates varus alignment.

[b] Kellgren and Lawrence (KL) grades of OA Severity: 0=no OA present, 1=doubtful narrowing of joint space and possible osteophytic lipping, 2=definite osteopytes, definite narrowing of joint space, 3=moderate multiple osteophytes, definite narrowing of joint space, some sclerosis and possible deformity of bone contour, 4=large osteophytes, marked narrowing of joint space, severe sclerosis and definite deformity of bone contour (Kellgren and Lawrence, 1957).

2. Methods

2.1. Study design

This study was approved by the institutional research ethics board. Thirty-nine subjects participated: 13 patients with valgus alignment ($>2^\circ$) and lateral compartment OA (valgus gonarthrosis), 13 patients with varus alignment ($<-2^\circ$) and medial compartment OA (varus gonarthrosis), and 13 asymptomatic controls with neutral alignment ($0\pm2^\circ$) (Table 1). Patients with varus and valgus gonarthrosis were matched for frontal plane malalignment $\pm2^\circ$ (yet in opposite direction). Patients underwent radiographic and gait analyses within 4 weeks prior to, and 6 months following, surgery. All patients with varus gonarthrosis received a medial opening wedge high tibial osteotomy (HTO). Seven patients in the valgus gonarthrosis group received lateral opening wedge HTO, while six received a lateral distal femoral opening wedge osteotomy. The general goal of osteotomy was to correct the preoperative deformity to achieve a postoperative limb alignment that was just beyond neutral. The specific angle was determined at the surgeon's discretion based on the magnitude of malalignment and the presence and severity of cartilage degeneration (visualized arthroscopically) in the opposite compartment of the original deformity (Birmingham et al., 2009; Fowler et al., 2000).

2.2. Limb alignment

Frontal plane alignment was measured from standing anteroposterior hip-to-ankle radiographs for patients (Specogna et al., 2007), and from joint centers calculated from the gait analysis static trial for controls (Mundermann et al., 2008). The MAA was defined as the angle formed between a line drawn from center of hip to center of knee and a line drawn from center of ankle to center of knee.

2.3. Gait

Gait was evaluated using an eight-camera motion capture system (Eagle, EvaRT 4.2, Motion Analysis Corporation, Santa Rosa, CA, USA), floor-mounted force plate (OR6, AMTI, Watertown, MA, USA) and modified Helen Hayes marker set (detailed methods previously described in Birmingham et al., 2007; Hunt et al., 2006; Jenkyn et al., 2008). Subjects walked barefoot at self-selected pace while 3D kinematic (60 Hz) and kinetic (1200 Hz) data were collected for a minimum of five trials.

Moments about the knee were calculated from the kinematic and kinetic data using inverse dynamics and were expressed as external moments relative to the tibial anatomical frame of reference (Orthotrak 6.0; Motion Analysis Corporation). Moments in each of the three orthogonal planes of movement were determined throughout stance phase and averaged over five trials of the same limb (operative limb, or limb closest to neutral for controls) while normalizing to body weight and height (%BW · Ht). The frontal plane knee moment waveform was then integrated with respect to time to calculate the frontal plane knee angular impulse (%BW · Ht · s) (Thorp et al., 2006b), summing the positive portions (adduction impulse) and negative portions (abduction impulse). Knee moments in all three planes were then normalized to 100% of stance and peak values in the first and second halves of stance were identified.

Table 2
Descriptive statistics (mean and standard deviation) for gait, and alignment variables.

Variables	Valgus Gonarthrosis (n=13)		Varus Gonarthrosis (n=13)		Controls (n=13)
	Before surgery	After surgery	Before surgery	After surgery	
Frontal plane knee angular impulse (%BW · Ht · s)[a]	−0.10 (0.49)	0.72 (0.39)	1.38 (0.40)	0.76 (0.38)	1.00 (0.19)
Knee adduction angular impulse (%BW · Ht · s)	0.24 (0.26)	0.75 (0.38)	1.42 (0.39)	0.81 (0.37)	1.04 (0.20)
Knee abduction angular impulse (%BW · Ht · s)	−0.34 (0.27)	−0.03 (0.02)	−0.04 (0.02)	−0.04 (0.03)	−0.04 (0.01)
Peak knee adduction moment (%BW · Ht)	0.88 (0.95)	1.60 (0.70)	3.09 (0.66)	1.65 (0.57)	2.24 (0.74)
Peak knee abduction moment(%BW · Ht)	−0.80 (0.63)	−0.05 (0.21)	−0.11 (0.15)	−0.22 (0.21)	0.04 (0.17)
Peak knee flexor moment (%BW · Ht)	0.36 (1.29)	0.25 (0.82)	0.42 (1.68)	0.37 (1.09)	0.97 (0.78)
Peak knee extensor moment (%BW · Ht)	−2.89 (1.45)	−2.41 (1.15)	−2.62 (1.28)	−2.24 (1.03)	−3.61 (1.25)
Peak knee external rotation moment (%BW · Ht)	0.54 (0.33)	0.35 (0.40)	0.33 (0.26)	0.41 (0.22)	0.46 (0.45)
Peak knee internal rotation moment (%BW · Ht)	−1.03 (0.52)	−1.21 (0.41)	−1.41 (−2.03)	−1.11 (0.25)	−1.53 (0.45)
Gait speed (m/s)	1.07 (0.13)	1.08 (0.19)	1.04 (0.21)	1.04 (0.18)	1.31 (0.15)
Mechanical axis angle(°)[b,*]	6.64 (3.85)	0.47 (3.73)	−6.72 (3.91)	0.54 (1.66)	−0.19 (0.85)

*Mechanical Axis Angle for control group were obtained from standing static gait trial.

[a] The frontal plane knee angular impulse (%BW · Ht · s) was defined as the sum of the integrals of the positive portion (adduction impulse) and negative portion (abduction impulse) of the frontal plane knee moment curve.

[b] Mechanical Axis Angle $>0^\circ$ indicates valgus alignment, Mechanical Axis Angle $<0^\circ$ indicates varus alignment.