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Leg kinematics and kinetics in landing from a single-leg hop for distance. A comparison between dominant and non-dominant leg

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Abstract

Background. Anterior cruciate ligament (ACL) deficiency can be a major problem for athletes and subsequent reconstruction of the ACL may be indicated if a conservative regimen has failed. After ACL reconstruction signs of abnormality in the use of the leg remain for a long time. It is expected that the landing after a single-leg hop for distance (horizontal hop) might give insight in the differences in kinematics and kinetics between uninjured legs and ACL-reconstructed legs. Before the ACL-reconstructed leg can be compared with the contralateral leg, knowledge of differences between legs of uninjured subjects is needed.

Methods. Kinematic and kinetic variables of both legs were measured with an optoelectronic system and a force plate and calculated by inverse dynamics. The dominant leg (the leg with biggest horizontal hop distance) and the contralateral leg of nine uninjured subjects were compared.

Findings. No significant differences were found in most of the kinematic and kinetic variables between dominant leg and contralateral leg of uninjured subjects. Only hop distance and hip extension angles differed significantly.

Interpretation. This study suggests that there are no important differences between dominant leg and contralateral leg in healthy subjects. As a consequence, the uninjured leg of ACL-reconstructed patients can be used as a reference. The observed variables of this study can be used as a reference of normal values and normal differences between legs in healthy subjects.

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Keywords: Single-leg hop for distance; Dominant/non-dominant; Hop-distance; ACL; Joint moments

1. Introduction

Athletes with a high activity level who sustain an anterior cruciate ligament (ACL) rupture may need a reconstruction of their ACL if a course of conservative rehabilitation has failed. ACL reconstruction is the treatment of choice to achieve a return back on pre-injury activity level (Deehan and Pinczewski, 2002; Fitzgerald et al., 2000; Shelton et al., 1997; Ciccotti et al., 1994; Andersson, 1993). Despite improvements in surgical techniques and

subsequent rehabilitation, abnormal motor control persists during functional activities (Shelbourne and Nitz, 1990). Abnormalities of the knee in walking up to six months after ACL reconstruction have been reported (Gokeler et al., 2003). Even less is known about the biomechanical characteristics during more demanding activities.

In most kinetic and kinematic studies about ACL-reconstructed subjects the involved leg and the uninjured leg are compared. A possible confounder is that differences in involved and uninjured leg, present before the ACL problems, are not taken in account. In general both legs are not equal. The question in this study therefore is: can the uninjured leg be used as reference regardless whether it was the dominant leg before the ACL-rupture or not? In the present study differences between dominant leg and

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contralateral leg in kinematics and kinetics will be studied of healthy subjects. The single-leg hop for distance is used as the movement for analysis. This movement is comparable with the high functional demands that are needed in sport. It is already used as a functional test for lower extremity and has turned out to be a reliable measure (Bolgla and Keskula, 1997; Ross et al., 2002). Wilk et al. (1994) used this measure specifically for ACL-reconstructed patients and found a moderate positive correlation between isokinetic peak torque and subjective knee scores with this hop test.

The expectation is that this horizontal hop will be useful in detecting changes in knee biomechanics. Sagittal kinematics and kinetics of the two legs of healthy subjects will be studied during landing. Landing is chosen because this stresses the knee most. Furthermore, data analysis of Juris et al. (1997) suggests that force absorption is more critical than force production to evaluate functional capacity of reconstructed ACL knees. With information of the sagittal kinematics and kinetics more insight in differences of dominant leg and contralateral leg in these determinants will be obtained. Kinematics variables that will be used are hop distance, hop height, peak flexion angles, peak extension angles and maximal excursion angles. Kinetics variables that will be studied are vertical and horizontal GRF (ground reaction force), extension moments and support moment.

The hypothesis is that there will only be small differences between the dominant leg and contralateral leg in the healthy subjects because there is no reason for different motor strategies during landing between limbs. A study of Ernst et al. (2000) supports this hypothesis because they did not find differences in kinetic variables with vertical jump and lateral step-up movements in healthy subjects. For the horizontal hop distance we expect to find a symmetry index above the 85% which Noyes et al. (1991) used as the limit for normal symmetry (Barber et al., 1990; Noyes et al., 1991). It is important for further research to know the magnitude of the differences between dominant leg and contralateral leg. When this is known, comparison between injured leg and contralateral leg in patients can be done with more confidence.

2. Methods

2.1. Subjects

Six healthy males and three females participated in the measurements. Mean age was 26.7 (5.9), with a mass of 79.24 (10.50) kg and a leg length of 100 (5.7) cm. (mean (SD)) The subjects had no injuries on the leg and back for at least three months, had no previous surgery on the leg, no history of neurological disease, no vestibular or visual disturbance. All the subjects were active in a sport in which leg movement is important, like soccer, baseball, korfbal and Judo. The study was approved by the local

ethics committee of the University of Groningen, The Netherlands. All subjects signed an informed consent.

2.2. Testing procedure

The subjects performed a modified maximal single-leg hop for distance as described by Daniel et al. (1988) (horizontal hop). This hop is performed with one leg and the target is a maximal horizontal distance. During this hop the arms are on the back and subjects wear sport shoes. Landing has to be on the force plate and the foot has to stay on the same place for at least one second after landing. Practice trials were performed till confidence with the hop was reached. Three trials of the single-leg hop for distance were performed to determine maximum distance. The leg with which the biggest horizontal distance was reached was defined as the dominant leg. These trials were also used to choose an adequate distance from the starting point to the force plate. Then the single-leg hop for distance was performed until ten correct recordings were obtained for each leg. First the dominant leg was measured and next the same procedure was followed for the contralateral leg.

2.3. Data acquisition

Position data of the lower extremity were collected by the OPTOTRAK[®] optoelectric camera system (Northern Digital Inc, Waterloo CA) with two cameras containing three sensors each. Optotrak measures the three-dimensional (3D) position of light-emitting diodes (LEDs) in a global reference frame. Sample frequency was 150 Hz. Three frames with four LED markers each were used for the pelvis, thigh and shank. Markers for the foot segment were directly attached to the shoe at the lateral side of the calcaneus. The frame for the pelvis was tightly attached using a photographer's belt. Frames (3.2 mm Aquaplastic) for the thigh and shank were attached with wide neoprene bandages and Velcro[®] fasteners.

Positions of bony landmarks were determined with a six LED probe. On the basis of these landmarks anatomical reference frames for the pelvis, thigh, shank and foot were defined according to Cappozzo et al. (1995). The global and the anatomical coordinate systems were defined according to the International Society of Biomechanics (ISB) recommendations: positive *x*, *y* and *z* point forward, upward and to the right, respectively.

For the calculation of the joint moments, centres were determined. For the hip and the knee they were functionally estimated while for the ankle an anatomical method was used. The functional hip centre of rotation was determined according to the method of Gamage and Lasenby (2002). The test movement was a rotation of the leg around the hip consisting of consecutive flexion/extension, ad-/abduction and circumduction movements. The method consists essentially of finding the midpoint of the best-fitting spheres for each of the markers. This was done for the pelvis markers with respect to the thigh. The results

are the coordinates of the functional hip joint centre with respect to the local coordinate system of the thigh. The knee joint centre and axis of rotation were determined with a variant of the same method of [Gamage and Lasenby \(2002\)](#) in which the axis of the best-fitting cylinder is determined. Test movement was a full knee flexion from a deep knee bend. Results are the direction of the joint axis of rotation, expressed as a unit vector, and one point on this axis. The knee joint centre was chosen as the point of intersection of this axis with the sagittal plane between the femoral condyles. These coordinates were determined with respect to the shank local coordinate systems.

The ankle joint centre was chosen as the midpoint between the medial and lateral malleoli, calculated from the shank marker data. Joint angles were calculated in the order *xyz* according to the method described by [Grood and Suntay](#) as suggested by the ISB ([Grood and Suntay, 1983](#); [Wu and Cavanagh, 1995](#)). The three components of the GRF and the position of the centre of pressure were recorded by a Bertec force plate (type 4060-08) at 750 Hz. Inertial parameters of the segments were calculated according to [de Leva \(1996\)](#).

Information collected so far was used to calculate the three-dimensional moments between the segments with inverse dynamics as described by [Hof \(1992\)](#). For calculation of the moments the segments are seen as coupled rigid bodies. In addition, the support moment was calculated from the sagittal extension moments. Extension moments are counted as positive ([Hof, 2000](#)):

$$M_{\text{Support}} = \frac{1}{2}M_{\text{Ankle}} + M_{\text{Knee}} + \frac{1}{2}M_{\text{Hip}} \quad (1)$$

Hop height was defined as displacement of the centre of gravity and calculated from the vertical momentum in landing.

$$m \cdot \Delta v = \int_{t_1}^{t_2} (F - mg) dt \quad (2)$$

$$h = \frac{\Delta v}{2 \cdot g} \quad (3)$$

2.4. Data analysis

The horizontal hop index was calculated as the horizontal hop distance of the contralateral leg divided by the distance of the dominant leg. For this the mean of the first three trials were used in which the dominant leg was determined. For other variables similar indices are calculated to enable a comparison between the different variables.

All analyses for moments and angles were done in the anatomical sagittal (*xy*) plane and are counted as positive for flexion angles and extension moments.

Force plate data and kinematic data were filtered by a second order low pass Butterworth filter with a cut-off frequency of 9.5 Hz, applied in a zero-phase forward and reverse digital filter. The cut-off frequency is in agreement with the cut-off used in the calculation of the accelerations

from the position data ([Bisseling and Hof, 2006](#)). After filtering, force plate data were sub-sampled to 150 Hz. GRF was normalized to body weight and moments were normalized for body weight $\times$ leg length to make inter subject comparison possible ([Hof, 1996](#); [Pierrynowski and Galea, 2001](#)). The raw vertical GRF was used to determine initial contact with the ground which is presented as zero time.

Maximum and minimum angles, excursion angles, maximum normalized vertical and horizontal GRF and maximum normalized joint and support moments during landing were used for statistical analysis. For the maximum moments the mean of a small interval (33 ms before and 33 ms after the peak) was used. For statistical analysis the mean values of 10 measurements of each subject were used as a value for group statistics. Standard deviations (SD) between the means of the nine subjects are given. When relevant, also SD of the ten horizontal hops of one subject, the ‘within subjects SD’, was determined as well. Paired student *t*-tests were used to test if there was any significant difference of the group means between limbs.

3. Results

3.1. Horizontal hop distance

The mean horizontal hop index was 95.5 (2.1) Mean distance of the dominant leg was 143.0 (6.8) cm compared to the contralateral leg: 136.8 (5.7) cm. This is a significant difference ($P < 0.01$).

3.2. Hop height

For the dominant leg a mean hop height of 12.2 (3.5) cm, within subjects SD 2.6 cm, was reached in a horizontal hop and for the contralateral leg this was 12.7 (2.3) cm, within subjects SD was 2.2 cm. This difference between legs was not significant. The mean index for hop height was 1.08 (0.18).

3.3. Joint angles

There was a typical sequence of movements from the knee joint during the horizontal hop. During take-off there is a major flexion, (1) in [Fig. 1](#), followed by extension (2). During flight the knee joint moves from extension at take-off to flexion during flight (3) followed by an extension in landing (4). Landing begins with an extended knee joint (5) which moves fast in to flexion (6). This flexion is again followed by an extension (7) as the subject ends with the knee more or less straight.

The variation in the hip and ankle between the ten landings is comparable to the variation in the knee angle between the ten landings. In [Fig. 2](#) the mean joint angles and within subjects SD of one person are shown for the 10 hops.

The mean and SD of the maximum and minimum joint angles in landing are shown in [Table 1](#). For the knee these correspond to arrows five and six in [Fig. 1](#), where the knee

Fig. 1. Sagittal knee flexion angles from one person in 10 horizontal hops. Vertical: knee flexion angle, 0 = fully extended. Horizontal: time, with touch down = 0.

Fig. 2. Mean sagittal knee, hip and ankle angles during a horizontal hop. Error bars show SD of 10 recordings of one subject (touch-down at 0 s).

moves from extension to flexion. The hip angle increases as well (ante-flexion). For the hip also the highest and lowest angles after landing are given. The highest angle is at the deepest position and the lowest is when landing is completed. The most dorsiflexed angle of the ankle is the landing on the heel at time 0 s. After this the ankle slows some plantar flexion during the flexion of the knee. This is the maximum of the ankle angle.

Hip angles were significantly less extended for the dominant leg ($P = 0.024$), while hip flexion and none of the other joint angles differed significantly.

Excursion angles are the differences between lowest and highest angles for each joint (Table 2). The differences between excursion angles of the legs were not significant.

3.4. Vertical ground reaction force

Shortly after landing there is a high peak in the vertical GRF which returns to bodyweight after an undershoot,

Table 1
Mean of maximal sagittal flexion and extension joint angles

	Dominant leg						Contralateral leg					
	Flexion			Extension			Flexion			Extension		
	deg	SD	ws*	deg	SD	ws*	deg	SD	ws*	deg	SD	ws*
Knee	65.2	7.2	5.0	17.1	3.7	2.5	66.3	10.3	7.5	18.6	7.7	3.7
Hip	77.6	13.6	6.8	29.6	17.4	16.3	68.6	26.2	17.4	16.6	24.0	27.0
Ankle	29.5	3.6	3.1	−.31	4.0	3.3	28.2	5.2	3.0	−2.0	5.7	3.3

Flexion is most flexed position, extension is most extended position. All flexion angles are counted as positive.

* ws SD is the within subjects SD.

Table 2
Maximal sagittal excursion angles

	Dominant leg			Contralateral leg			Indices	
	deg	SD	ws* SD	deg	SD	ws* SD	deg	SD
Knee	47.7	6.7	5.4	47.8	8.7	6.3	1.00	0.09
Hip	48.0	20.2	18.0	52.0	23.76	37.10	1.11	0.34
Ankle	29.8	2.8	4.3	30.8	4.7	4.3	1.03	0.09

Excursion angles are the differences between lowest and highest angles for each joint.

* ws SD is the within subjects SD.

Fig. 3. Vertical ground reaction force of ten measurements from one subject during horizontal hops (touch-down at 0 s). The small undershoot shortly before landing is an artefact due to the filtering procedure.

which means that the acceleration of the centre of mass was downward. Fig. 3 shows the distribution of the horizontal GRF of ten hops from one object.

Mean normalized vertical GRF for the dominant leg was 2.45 (0.30), within subjects SD 0.13, and for the contralateral leg 2.52 (0.33), within subjects SD 0.12 (normalized for body weight). The difference was not significant. The index for GRF vertical was 1.03 (0.045).

3.5. Horizontal ground reaction force

The horizontal GRF had comparable characteristics as the vertical GRF but without an undershoot, a lower peak and it returns to zero after about 0.5 s. Mean normalized horizontal GRF for the dominant leg was 0.95 (0.16), within subjects SD 0.073, and for the contralateral leg 0.94 (0.17), within subjects SD 0.078 (normalized for body weight). The difference was not significant. The index for the horizontal GRF was 0.99 (0.071).

3.6. Joint moments

Fig. 4 shows the joint moments and the calculated support moment for one representative jump. Shortly after landing there is a clear peak moment in each joint related to the impact of landing.

Fig. 4. Representative sagittal joint moments and support moment curve for landing of one horizontal hop (touch-down at 0 s). Moments in take-off have not been calculated, as the subject was then off the force plate. The hip and knee flexion moments before touch-down are related to a backward acceleration of the leg.

Table 3
Mean sagittal maximal normalized moments and moment indexes

	Best leg			Contralateral leg			Index	
	M	SD	ws* SD	M	SD	ws* SD		SD
Knee	0.27	0.044	0.029	0.28	0.059	0.028	1.04	0.19
Hip	0.28	0.114	0.053	0.24	0.093	0.037	0.92	0.23
Ankle	0.11	0.028	0.042	0.11	0.039	0.043	1.01	0.28
Support	0.41	0.052	0.034	0.42	0.066	0.031	1.01	0.16

Moment (*M*) is normalized for weight $\times$ leg length. All extension moments are counted as positive.

* ws SD is the within subjects SD.

The calculated means of the maximum normalized moments (moment/(bodyweight $\times$ leg length)) during landing for the nine subjects are presented in Table 3. For the knee this is extension moment, for the hip retro-flexion (extension) moment and for the ankle plantar flexion (extension) moment. None of the differences in moments between legs was significant.

3.7. Indices

The bars in Fig. 5, give an overview of all calculated indices. An index under 1.0 means that the dominant leg had a higher value. None of the indices was significantly different from 1.

4. Discussion

In the present study, we have defined the dominant leg as the leg with which the largest horizontal hop distance was reached. This has to be distinguished from the pre-

Fig. 5. All calculated indices with SD (dominant leg/contralateral leg).

ferred leg. The preferred leg is the leg that is used to manipulate an object. A review of Peters (1988) showed already that in high jumps most athletes preferred the left leg while in the long jump it was equally divided. In this study 3 of 9 subjects had the biggest hop distance with their left leg.

The high hop index (mean 95.5%) for distance we found is in accordance with the index Ageberg et al. (2001) found for a sportive active group (mean of 94.2%). That the present group was an active athletic population can be an important reason why the index is that high. An active group was chosen because most ACL-reconstructed patients are active in sports and want to become active again. This high hop index explains why only few differences were found in the observed kinematics and kinetics for the dominant and contralateral leg.

The mean horizontal hop distance of subjects in this study (143 (17) cm/137 (6) cm) was low compared to that of Ageberg et al. (2001): 203 (21) cm for men and 163 (20) cm for women. An explanation can be that in the study of Ageberg et al. (2001), subjects were allowed to use their arms freely in contrast with this study where arms had to be on the back. A study of Ashby and Heegaard (2002) showed that restricted arm movement in standing long jumps account for 21.2% less distance in contrast with free arm movement.

Values of the peak vertical GRF were in accordance with Webster et al. (2004). They found for horizontal hops a normalized GRF of 2.5 in non-operated limbs of ACL-reconstructed subjects. This is exactly what is found in this study for the dominant leg. Knee moments and angles differed slightly with the results of Webster et al. (2004) for

the non-operated limb. For maximal angles and moments in our study respectively 65.2 (7.2) deg and 0.27 (0.044) normalized moment was found. In the study of Webster et al. (2004) angles and moments were respectively 52.5 (5.6) deg and 0.21 (0.040) normalized moment. The difference was possibly due to the fact that the horizontal hop distance in the study of Webster et al. (2004) was equal to leg length. Leg length was not reported in that study but will be around 100 cm. This distance is clearly less than the distance our subjects hopped. An other difference was that in our study subjects wore sport shoes and in the study of Webster et al. (2004) hops were done barefoot. It is remarkable that in contrast to the knee moment and angle there was no difference between studies in the peak vertical GRF. In our study hop height is a good indication of the vertical momentum because hop height is directly calculated from the vertical momentum. To our knowledge there are no results published of hop height or vertical momentum in other horizontal hop studies. For horizontal GRF we also did not find other studies with published results for the horizontal hop.

Joint angles found in a study of Rudolph et al. (2000) for uninjured subjects during landing after a horizontal hop were different from ours. They found the hip, knee and ankle angle to be smaller. This difference was possibly due to differences in execution of the horizontal hop. In the study of Rudolph et al. (2000) subjects had to hop onto the force plate and immediately off, while in our study the hop was considered correct when after landing there was no displacement of the landing foot. This difference is important because when hopping ahead after landing the horizontal velocity does not need to slow down completely. It is to be expected that when breaking forces are lower, joint angles will be lower as well. Differences in anatomical definitions of the angles may contribute to differences as well, therefore joint excursion angles could have surplus value because they are not heavily based on these definitions.

In spite of the significant difference in hop distance between legs, the only other significant difference was the maximal hip extension angle. The hip was significantly less extended for the dominant leg compared to the contralateral leg, the difference was 13.8 deg ($P = 0.015$). This means that after landing with the dominant leg the posture is less erect in the end. The difference of the excursion angle of the hip was just 4.0 deg less for dominant leg in compared to contralateral leg. This is very low and probably clinically not significant.

The measurements were done after confidence with the horizontal hop was reached, but there is still a possible confounding effect of learning. In general the within subjects SD was not high, which suggests that learning and fatigue effects are minor in hops of one leg. Learning of horizontal hopping with the dominant leg might have had effect on the contralateral leg, which would mean that the contralateral leg could possibly perform the hops better. Learning thus would give a lower difference between legs. Randomizing of order of the legs was not done because with

ACL-reconstructed patients, patients first have to get confidence in doing the movement with the non-operated leg. Only after the non-operated leg has been used it is justified to do the movement with the reconstructed leg. So, for the purpose of future comparison between normal subjects and ACL-reconstructed subjects the order of dominant leg first and contralateral leg next is maintained.

The SD of the excursion angles of the hip were high compared to the other joints. It seems that the hip excursion differs considerably between different movements. Also the SD's in moments, flexion and extension angles are big for the hip. Probably the big SD's of the hip have to do with the contribution to the balance of the trunk. For ankle there is also a big SD within subjects for the moments. We expect that this is also a consequence of the contribution of the ankle to the balance.

Indices in Fig. 5 summarizes the results of this study. The figure shows no significant differences between dominant leg and contralateral leg. It supports the idea that the contralateral leg can be used as reference leg of ACL-reconstructed subjects.

5. Conclusion

The question in this study was: can the uninvolved leg be used as reference regardless whether it was the dominant leg before the ACL-rupture or not? Only hop distance and hip extension angles differed significantly. This study suggests that there are no important differences between dominant leg and contralateral leg in healthy subjects. As a consequence, the uninvolved leg of ACL-reconstructed patients can be used as a reference. The observed variables of this study can be used as reference values of normal values and as reference values of normal differences between legs in healthy subjects.

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