Towards ambulatory assessment of spinal loading in the field

Faber, G.S.

2010

Chapter 7

Determination of joint moments with instrumented force shoes in a variety of tasks

Faber GS, Kingma I, Schepers HM, Veltink PH & van Dieën JH

Submitted

ABSTRACT

Force plates (FPs), measuring ground reaction forces (GRFs), are often used in inverse dynamics analyses to determine joint loading. As an alternative, instrumented force shoes (FSs) can be used, which have the advantage over FPs that they do not constrain foot placement. This study tested the FS system in one normal weight subject (77kg) performing 19 different lifting, pushing & pulling and walking tasks. Kinematics were measured with an optoelectronic system and the GRFs and the positions of the centre of pressure (CoP) were synchronously measured with FPs and FSs. Differences between the outcomes of the two measurement systems and the resulting ankle and L5/S1 joint moments were determined at the instant of the peak GRF (DaPF). For most lifting and pushing & pulling tasks, good agreement was found between the FP and FS measurements: GRF DaPF remained below 3% body weight, CoP DaPF remained below 10mm, ankle moment DaPF remained below 7% of the peak total ankle moment that occurred during normal walking and L5/S1 moment DaPF remained below 7% of the peak total L5/S1 moment that occurred during normal symmetric lifting. Only in maximal pushing tasks more substantial differences were found. For the walking tasks, peak vertical GRFs were somewhat underestimated. However, differences in ankle and L5/S1 moments remained small, i.e. DaPF below 7% of the total peak moments. In conclusion, except for the maximal pushing tasks, the FSs were capable of measuring the GRFs and CoP and the resulting ankle and L5/S1 moments with satisfactory accuracy.

INTRODUCTION

Many studies have used force plates (FPs) to measure ground reaction forces (GRFs), as input in calculation of spinal moments using inverse dynamics (Lavender et al., 1999; Gagnon, 2005; Faber et al., 2009b). A disadvantage of FPs is that foot placement is constrained by their size and location. As an alternative, instrumented force shoes (FSs) can be used, which do not have this disadvantage. Such shoes have been shown to allow accurate measurement of GRFs and calculation of ankle moments in walking (Veltink et al., 2005; Liedtke et al., 2007; Schepers et al., 2007). The question is, however, if the accuracy is sufficient during tasks such as lifting, pushing and pulling, in which the FSs are loaded differently (e.g. higher horizontal forces). Furthermore it is not obvious that spinal moments can be estimated with sufficient accuracy. Because the spine is located higher above the ground than the ankle joint, moment estimates are more sensitive to errors in the direction of the measured GRFs.

The present study explored the performance of the FS system in a variety of tasks. GRFs and the positions of the centre of pressure (CoP) were synchronously measured with FPs and FSs, and the outcomes of the two measurement systems and the resulting moments about the ankle and L5/S1 joints were compared.

METHODS

Experimental procedure

After signing informed consent, approved by the local ethics committee, 1 healthy male subject (mass = 77kg; height = 179cm) performed 19 tasks, which can be subdivided in 3 categories: lifting, pushing & pulling, and walking (Table 7-1).

Table 7-1. *Description of the 19 tasks performed by the subject in the present study. The "direction of action" indicates the direction in which the task was executed.*

Tasks	Description	Direction of action
<u>**Lifting tasks**</u>		
Normal symmetric lift	Lifting a box from ground level using a symmetric lifting technique	x
Fast symmetric lift	Same as the normal symmetric lift but then fast	x
Normal asymmetric lift	Lifting a box from ground level placing the left foot in front of the right one	y
Fast asymmetric lift	Same as the normal asymmetric lift but then fast	y
<u>**Pushing & pulling tasks**</u>		
Normal symmetric push	Pushing a stationary cart using a symmetric posture	x
Maximal symmetric push	Same as the normal symmetric push but then pushing maximally	x
Normal asymmetric push	Pushing a stationary cart placing the left foot in front of the right one	y
Maximal asymmetric push	Same as the normal asymmetric push but then pushing maximally	y
Normal symmetric pull	Pulling a stationary cart using a symmetric posture	x
Maximal symmetric pull	Same as the normal symmetric pull but then pushing maximally	x
Normal asymmetric pull	Pulling a stationary cart using placing the left foot in front of the right one	y
Maximal asymmetric pull	Same as the normal asymmetric pull but then pushing maximally	y
<u>**Walking tasks**</u>		
Normal walking	Walking normally hitting the force plate with the right foot	-y
Fast walking	Walking fast hitting the force plate with the right foot	-y
Obstacle avoidance	Walking, avoiding an obstacle by making a sidestep and hitting the force plate	-y
Normal stair ascent	Walking up-stairs and hitting the force plate with the right foot just before first step	-y
Fast stair ascent	Same as the normal stair ascent but then fast	-y
Normal stair descent	Walking down-stairs and hitting the force plate with the right foot just after the last step	-y
Fast stair descent	Same as the normal stair descend but then fast	-y

Data collection and pre-processing

The GRFs (and moments) were recorded by two FPs (Kistler, 9218B) and two FSs with 3D force/moment sensors (FMsensors) mounted to the sole beneath the heel and forefoot of each shoe (Veltink et al., 2005; Liedtke et al., 2007; Schepers et al., 2007). FP signals were sampled at 200 samples/s. Given limitations of the current configuration of the FS system (Schepers et al., 2009), FS signals were sampled at 50 samples/s. Marker clusters containing three Optotrak markers (Northern Digital Inc., Canada) defined the kinematics (at 50 samples/s) of the pelvis and lower extremity segments and the FMsensors (Figure 7-1). All signals were bi-directionally low-pass filtered with a second-order Butterworth filter, at a cut-off frequency of 15 Hz. The anatomical coordinate systems (CSs) of the measured segments were related to the marker cluster CSs, by making short recordings of anatomical landmarks using a probe containing six markers (Cappozzo et al., 1995).

Alignment of FMsensor CSs with the marker cluster CSs

Each of the four FMsensors was rigidly attached to an Optotrak marker cluster (Figure 7-1). For each FMsensor, alignment of the marker cluster CS with the FMsensor's CS was initially realised by probing the four corners of the FMsensor. Subsequently, for each FMsensor, a reference measurement was performed in which the subject was standing upright, while only that FMsensor contacted the FP. Using these reference measurements, the orientation matrix of each FMsensor was optimally rotated around it's local horizontal axes such that the sum of the error in all three directions was minimised. For further analyses, these optimised CSs were used. This procedure aimed at minimising projection errors of vertical forces on horizontal axes, as these can have substantial effects at higher joints, because of the large moment arms of horizontal forces.

Biomechanical analyses

FP and FS based GRF and CoP data were expressed in the global CS (see Figure 7-1) and combined with segment kinematics to calculate moments at the left and right ankle and the L5/S1 joint, using 3D inverse dynamics (Kingma et al., 1996). Note that including moments caused by segment kinematics did not affect the difference between the FP and FS based moment calculations, because these moments were identical in both inverse dynamics calculations. To obtain the 3D components of the net moments, the ankle and L5/S1 moments were projected onto the calf and pelvis CSs, respectively. The directions of the anatomical axes were as follows: x-axis forward, z-axis upward and y-axis leftward.

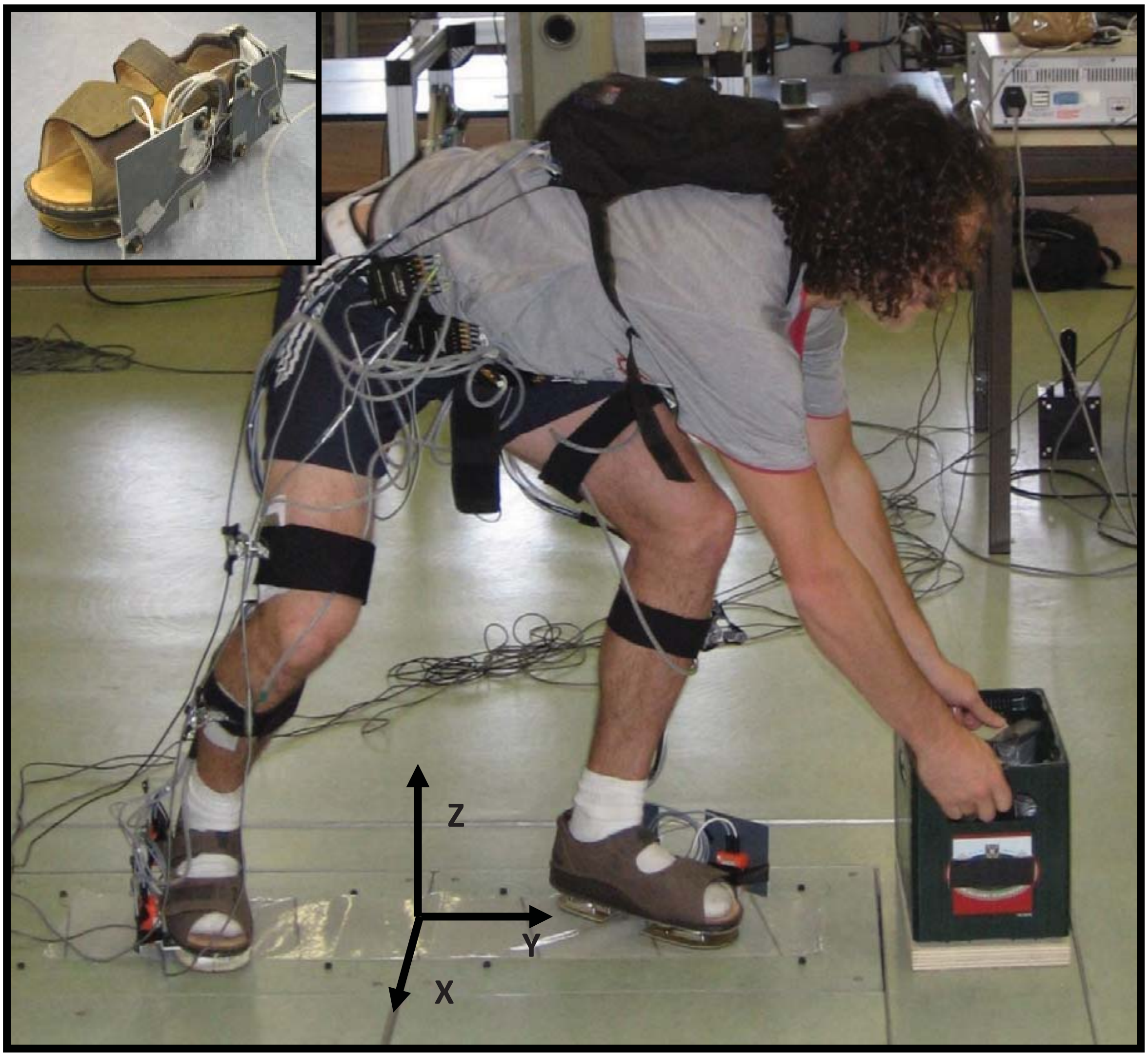

Figure 7-1. *Photo of the subject, equipped with Optotrak marker clusters and wearing the FSs, performing the normal asymmetric lifting task. The global coordinate system (CS) in which the FP and FS measurement outcomes were expressed is indicated in between the two FPs. In order to get the total FS GRF, the local forces and moments measured by each FMsensor were rotated to the global CS (using the orientation of each FMsensor) and subsequently summed. The combined CoP was obtained by solving a moment balance about the origin of the CS, translating the CoP in the global horizontal plane such that the moments around the horizontal axes were zero. The same procedure was applied to calculate the combined GRF and CoP of the two FPs. The only difference was that the orientation of the FPs was fixed in the global CS (obtained by probing its corners) and therefore did not need to be captured during the experiment. In the upper left corner an enlarged photo of the left FS equipped with Optotrak marker clusters is displayed.*

Data synchronisation

To synchronise force signals, a pulse was send out by the FP's AD board. This pulse was recorded by the FS system and started sampling of the Optotrak system. Because FS data were measured at 50 Hz, synchronisation of the force data could be off by up to 10 ms. To correct for this synchronisation error, FS, FP and Optotrak data were resampled at 1000 Hz using spline interpolation, and the FS data were shifted in time such that the correlation between the total net forces measured by both systems was maximised.

During data analysis it emerged that sampling by the Optotrak system started a little after it received the pulse from the FP system. Whereas this barely affected the data analysis based on FP data, it did cause substantial projection errors in FS based forces, because orientation matrices measured at wrong instants of time were applied to rotate the local FS data to the global reference CS. Therefore, Optotrak data were shifted with respect to the FP and FS data such that the correlation between the 3D GRFs, measured by the FPs and FSs was maximised.

Data reduction

For all time series of the GRF, CoP and ankle and L5/S1 moments, the average absolute difference (AAD) and the difference at the instant of the peak total GRF (DaPF) were determined. For the CoP, FP and FS measurements were only compared for the part of the data that the vertical GRF exceeded 40N. For the ankle, moments were calculated at the left and right side but results are only reported for the leg with the largest total GRF.

RESULTS

For a representative selection of the 19 tasks, the time series of the GRF, CoP and ankle and L5/S1 moments measured are shown in Figure 7-2. For all 19 tasks, the AADs and the DaPF of these variables are presented in Table 7-2. Because DaPF were generally more substantial than the AADs, only the former will be discussed here.

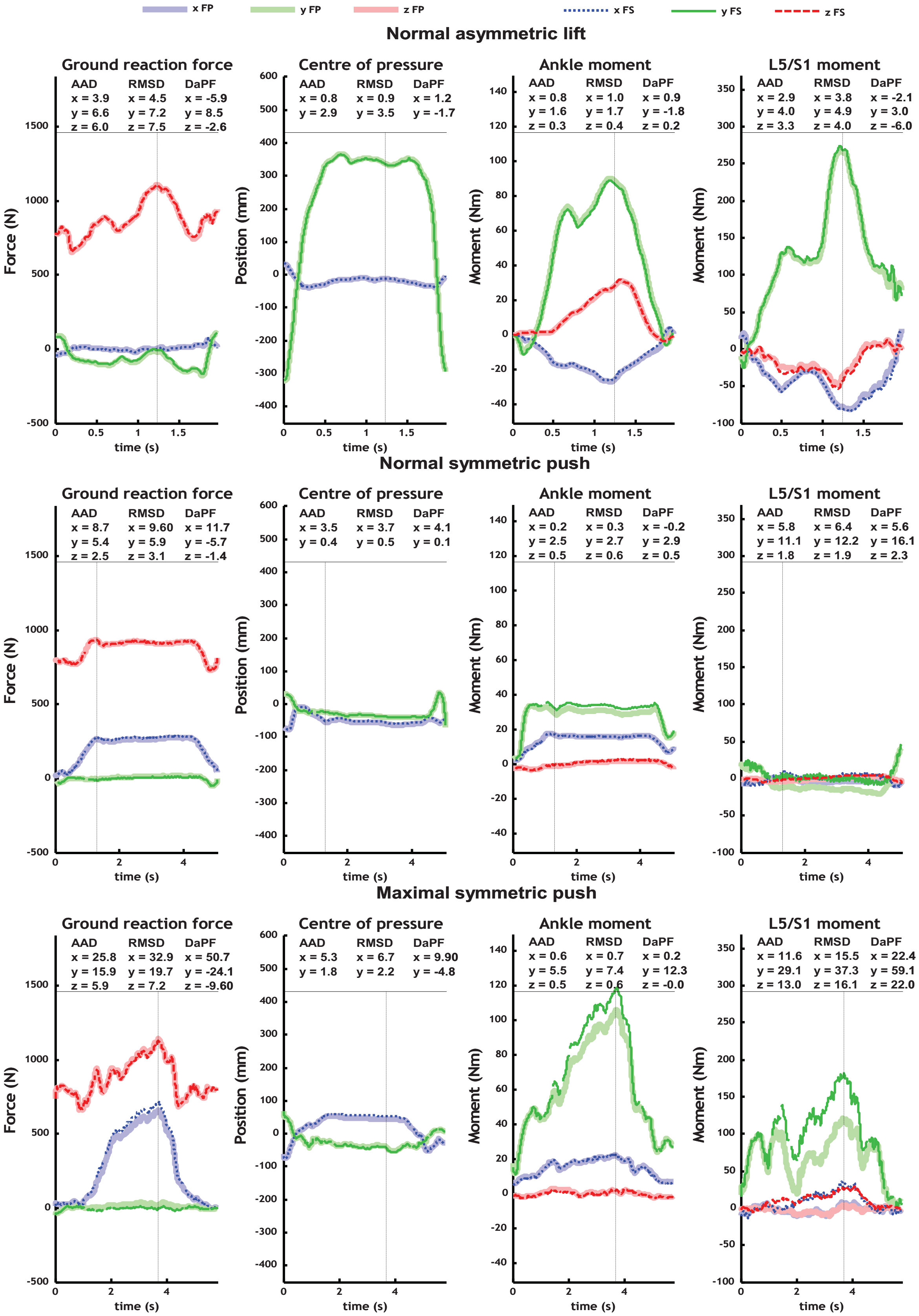

Figure 7-2. *Time series of the GRFs, CoP and ankle and L5/S1 moments measured using the FP and FS data for a representative selection of the 19 tasks. In the upper part of each plot, differences between the outcomes of the two measurement systems are indicated. The vertical line in each plot indicates the instant of peak total GRF.*

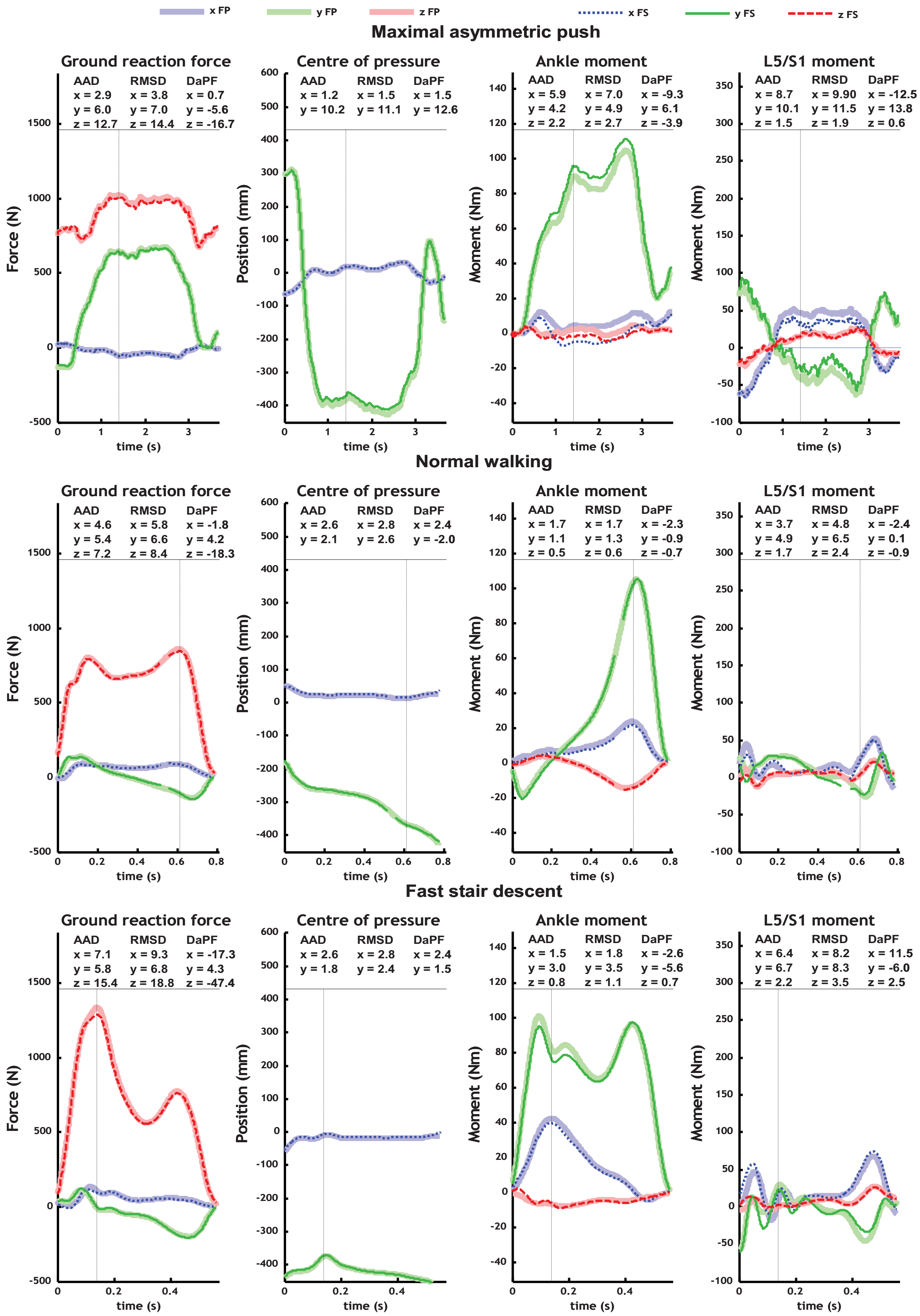

Figure 7-2 continued. *Time series of the GRFs, CoP and ankle and L5/S1 moments measured using the FP and FS data for a representative selection of the 19 tasks. In the upper part of each plot, differences between the outcomes of the two measurement systems are indicated. The vertical line in each plot indicates the instant of peak total GRF.*

Table 7-2. *Average absolute differences (AADs) and differences at the instant of the peak GRF (DaPF) in the GRFs, CoP and ankle and L5/S1 moments for all 19 tasks performed by the subject.*

Average absolute differences (AAD)

	GRF (N)			CoP (mm)		Ankle moment (Nm)			L5/S1 moment (Nm)		
	x	y	z	x	y	x	y	z	x	y	z
Lifting tasks											
Normal symmetric lift	3	3	2	1.2	1.5	0.4	0.7	0.4	1	4	2
Fast symmetric lift	3	2	4	1.2	1.9	0.3	0.5	0.2	1	4	1
Normal asymmetric lift	4	7	6	0.8	2.9	0.8	1.6	0.3	3	4	3
Fast asymmetric lift	8	6	6	0.8	3.3	1.2	1.9	0.7	5	6	4
Pushing & pulling tasks											
Normal symmetric push	9	5	3	3.5	0.4	0.2	2.5	0.5	6	11	2
Maximal symmetric push	26	16	6	5.3	1.8	0.6	5.5	0.5	12	29	13
Normal asymmetric push	6	3	6	1.7	5.8	0.7	3.3	0.6	4	5	3
Maximal asymmetric push	3	6	13	1.2	10.2	5.9	4.2	2.2	9	10	2
Normal symmetric pull	3	4	4	3.3	3.4	0.6	2.4	0.7	3	3	4
Maximal symmetric pull	8	8	6	3.9	3.7	1.5	0.3	2.0	4	6	7
Normal asymmetric pull	11	11	9	0.5	5.3	2.4	1.6	1.6	2	14	9
Maximal asymmetric pull	9	9	11	0.5	7.9	2.5	3.1	1.0	4	9	8
Walking tasks											
Normal walking	5	5	7	2.6	2.1	1.6	1.1	0.5	4	5	2
Fast walking	3	8	7	3.1	2.0	2.3	2.0	0.3	3	8	1
Obstacle avoidance	5	10	17	2.4	1.6	2.4	3.2	1.0	5	14	3
Normal stair ascent	5	6	12	0.8	0.9	0.4	1.6	0.3	4	7	1
Fast stair ascent	3	5	17	0.5	2.7	0.8	3.2	0.3	4	8	2
Normal stair descent	5	4	16	2.2	2.5	1.5	3.2	0.5	4	5	2
Fast stair descent	7	6	15	2.6	1.8	1.5	3.0	0.8	6	7	2

Differences at peak GRF (DaPF)

	GRF (N)			CoP (mm)		Ankle moment (Nm)			L5/S1 moment (Nm)		
	x	y	z	x	y	x	y	z	x	y	z
Lifting tasks											
Normal symmetric lift	7	-6	-8	0.9	1.3	-0.1	0.7	-0.7	0	4	3
Fast symmetric lift	-1	3	-14	0.1	1.8	-0.4	-2.0	-0.8	-4	-4	-2
Normal asymmetric lift	-6	9	-3	1.2	-1.7	0.9	-1.8	0.2	-2	3	-6
Fast asymmetric lift	-11	10	-7	1.2	-2.3	1.3	-3.2	0.6	-5	-2	-9
Pushing & pulling tasks											
Normal symmetric push	12	-6	-1	4.1	0.1	-0.2	2.9	0.5	6	16	2
Maximal symmetric push	51	-24	-10	9.9	-4.8	0.2	12.3	0.0	22	59	22
Normal asymmetric push	11	-3	7	1.3	7.0	-0.7	5.4	-0.6	9	5	6
Maximal asymmetric push	1	-6	-17	1.5	12.6	-9.3	6.1	-3.9	-12	14	1
Normal symmetric pull	1	5	1	-3.6	3.4	-1.2	-2.9	-0.9	-6	-2	-3
Maximal symmetric pull	4	-5	7	-5.6	4.2	0.2	-0.8	2.5	-3	0	3
Normal asymmetric pull	11	12	10	0.7	-6.2	2.7	-2.5	1.7	1	15	9
Maximal asymmetric pull	5	13	14	0.5	-9.1	2.2	-3.5	0.9	-3	12	4
Walking tasks											
Normal walking	-2	4	-18	2.3	-2.0	-2.4	-0.9	-0.7	-2	0	-1
Fast walking	-8	10	-22	2.3	-0.8	-1.6	-3.0	-0.1	3	-4	0
Obstacle avoidance	1	6	-22	3.2	2.4	-4.4	-4.3	1.0	-5	-15	-2
Normal stair ascent	5	-2	-20	0.4	0.3	0.5	-2.1	0.5	4	-1	1
Fast stair ascent	-5	-10	-41	0.4	-1.3	-1.7	-7.0	-0.1	-8	-14	-1
Normal stair descent	3	4	-36	2.0	3.1	-3.7	-6.9	0.8	-8	-14	-1
Fast stair descent	-17	4	-47	2.4	1.5	-2.6	-5.6	0.7	11	-6	3

DaPF in the GRFs, expressed as percentage body weight (%BW, BW = 755N), remained below 3%BW (23N) for almost all tasks, except maximal symmetric pushing (6.8%BW for the forward direction), fast stair ascent (-5.5%BW), normal stair descent (-4.9%BW) and fast stair descent (-6.4%BW). Notably, for all walking tasks DaPFs were mainly large for the vertical direction and indicated an underestimation. For the CoP, the DaPF exceeded 10 mm only during maximal asymmetric pushing (13mm). DaPF in ankle moments, expressed as percentage of the peak total ankle moment that occurred during normal walking (%PAM_{NW}, PAM_{NW} = 108Nm), remained below 7%PAM_{NW} (7.5Nm) for all tasks except maximal symmetric pushing (11.4%PAM_{NW}) and maximal asymmetric pushing (-8.7%PAM_{NW}). DaPF in L5/S1 moments, expressed as percentage of the peak total spinal moment that occurred during normal symmetric lifting (%PSM_{NSL}, PSM_{NSL} = 283Nm), remained below 7%PSM_{NSL} (20Nm) for all tasks except maximal symmetric pushing (10.3%PSM_{NSL}).

DISCUSSION

Overall FP and FS measurements showed good agreement. For most lifting and pushing & pulling tasks, differences between FP and FS measurements were small (GRF DaPF <3%BW; CoP DaPF <10mm; ankle moment DaPF <7%PAM_{NW}; L5/S1 moment DaPF <7%PSM_{NSL}). Only for maximal symmetric and asymmetric pushing more substantial differences were found, probably because of relatively high FMsensor loading in two or more directions simultaneously (>50% of measurement range), resulting in some crosstalk.

For the walking tasks, the peak vertical GRFs were consistently underestimated, probably due to high FMsensor loading in this direction (70% of measurement range for normal walking up to 109% for fast stair ascent). However, because no substantial differences in horizontal GRFs and CoP were found between FS and FP measurements for these tasks, differences in ankle and L5/S1 moments remained small (ankle moment DaPF <7%PAM_{NW}; L5/S1 moment DaPF <7%PSM_{NSL}). Schepers et al. (2007) found comparably small root-mean-square differences (RMSDs, see Figure 7-2) between FP and FS measurements during normal walking when measuring FMsensor orientations with inertial sensors. Another study (Liedtke et al., 2007) found about three times larger RMSDs, when measuring FMsensor orientation with a passive optoelectronic system, which may be due to the precision of the kinematic data or the accuracy of the synchronisation. It should be noted that accurate synchronisation is more important when using FSs than when using FPs because kinematic data are used to rotate local FMsensor data to the global CS (Figure 7-3 shows an example of the effect of a 40ms delay of the kinematic data).

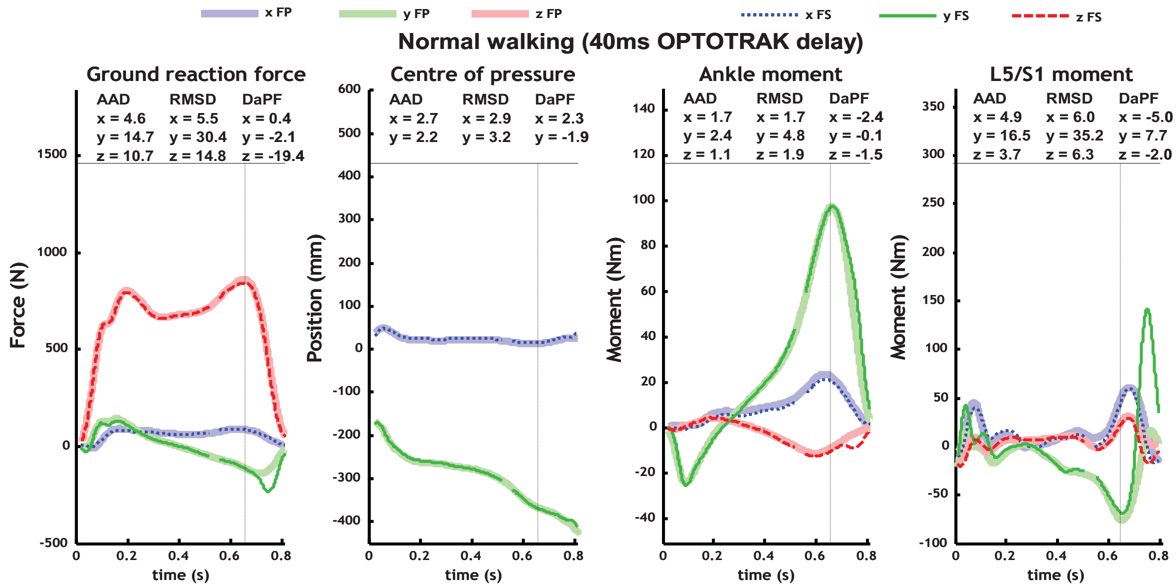

Figure 7-3. *Example of the effect of a 40ms delay of the kinematic data in the normal walking trial (compare with Figure 7-2 continued) on the time series of the GRFs, CoP and ankle and L5/S1 moments measured using the FP and FS data. In the upper part of each plot, differences between the outcomes of the two measurement systems are indicated. The vertical line in each plot indicates the instant of peak total GRF.*

A limitation of the present study is that only one subject was used. While most subject characteristics are unlikely to affect FS measurement errors, the results indicate that the magnitude of FMsensor loading does, so especially subject mass may affect measurement errors, as heavier subjects may more often exceed the linear range of the FMsensor.

CONCLUSION

In conclusion, except for maximum pushing tasks, the FSs were capable of measuring the GRFs and CoP and the resulting ankle and L5/S1 moments with satisfactory accuracy.

ACKNOWLEDGEMENTS

This study is part of the FreeMotion project, funded by the Dutch Ministry of Economic Affairs and SenterNovem.