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# ***Chapter 8***

## **Bottom-up estimation of joint moments during manual lifting using orientation sensors instead of position sensors**

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## ABSTRACT

*L5/S1, hip and knee moments during manual lifting tasks are, in a laboratory environment, frequently established by bottom-up inverse dynamics, using force plates to measure ground reaction forces (GRFs) and an optoelectronic system to measure segment positions and orientations. For field measurements, alternative measurement systems are being developed. One alternative is the use of small body-mounted inertial/magnetic sensors (IMs) and instrumented force shoes to measure segment orientation and GRFs, respectively. However, because IMs measure segment orientations only, the positions of segments relative to each other and relative to the GRFs have to be determined by linking them, assuming fixed segment lengths and zero joint translation. This will affect the estimated joint positions and joint moments. This study investigated the effect of using segment orientations only (orientation based method) instead of using orientations and positions (reference method) on three-dimensional joint moments. To compare analysis methods (and not measurement methods), GRFs were measured with a force plate and segment positions and/or orientations were measured using optoelectronic marker clusters for both analysis methods. Eleven male subjects lifted a box from floor level using three lifting techniques: a stoop, a semi-squat and a squat technique. The difference between the two analysis methods remained small for the knee moments: <4%. For the hip and L5/S1 moments, the differences were more substantial: up to 8% for the stoop and semi-squat techniques and up to 14% for the squat technique. In conclusion, joint moments during lifting can be estimated with good accuracy at the knee joint and with reasonable accuracy at the hip and L5/S1 joints using segment orientation and GRF data only.*

## INTRODUCTION

L5/S1, hip and knee moments during manual lifting tasks have often been assessed in the laboratory using one or more force plates measuring ground reaction forces (GRFs) and an optoelectronic system measuring positions and orientations of body segments (e.g. Faber et al., 2007). The usability of such systems for field measurements is limited by the restricted measurement volume of the optoelectronic system and the constraints on foot placement imposed by the force plates.

A possible alternative measurement system that does not have these limitations consists of instrumented shoes measuring GRFs (Schepers et al., 2007) and small body-mounted inertial/magnetic sensors (IMSS) measuring segment kinematics (Luinge & Veltink, 2005). However, IMSS measure only the orientations and not the positions of segments. Therefore, the positions of the segments relative to each other and relative to the GRFs have to be determined by linking the segments to each other, assuming fixed segment lengths and joints that do not allow translation.

Since in reality joint rotation centres are not fixed (van den Bogert et al., 2008), and because of soft-tissue artefacts (Leardini et al., 2005), errors in estimated joint positions are inevitable. These errors are also present when measuring with an optoelectronic system. However, when only orientations of segments are available, position errors present in each segment will add up when linking segments to each other (Figure 8-1).

The present study investigated the effect of the additional position error resulting from using only segment orientation (linking the segments using fixed segment lengths) instead of segment position and orientation on the estimated knee, hip and L5/S1 moments during manual lifting. Three different lifting techniques were studied to test whether the amount of knee flexion affects the discrepancy between the two analysis methods. To purely test the effect of analysis method (and not of measurement method), GRFs were measured with a force plate and segment positions and/or orientations were measured using optoelectronic marker clusters for both analysis methods.

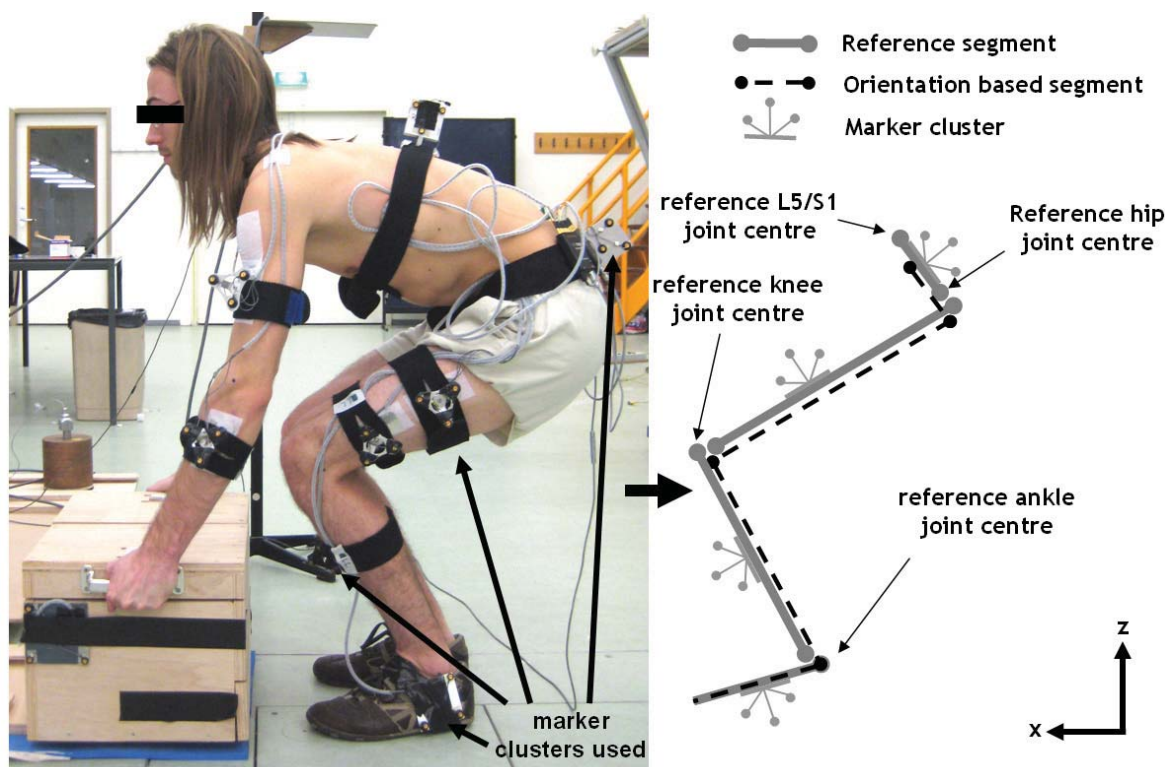
# METHODS

## Subjects and procedure

Since the current study was the first to investigate the effects of using orientation instead of position sensors on bottom-up estimation of joint moments, a relatively lean male subject population was chosen to minimise the interference of large soft-tissue artefacts and errors in joint centre localisation. After signing an informed consent, 11 healthy male subjects (age:  $27.4 \pm 4.3$  years; mass:  $73.8 \pm 8.9$ kg, height:  $181.0 \pm 5.2$ cm) participated in the experiment, which was approved by the local ethics committee. Subjects performed a lifting task in which a 10-kg box was lifted from an initial handle height of 30 cm. All subjects performed this lifting task with a stoop (knees extended), a semi-squat (bending the knees to about  $90^\circ$ ) and a squat technique (bending the knees, while holding the trunk as upright as possible).

## Data collection

GRFs beneath the left foot were measured (200 samples/s) by a Kistler force plate and the positions and orientations of the box, the pelvis and the left thigh, calf and foot (+ shoe) were measured (75 samples/s) by marker clusters containing 3 Optrak markers (Northern Digital Inc., Canada). Marker clusters were taped and strapped to body segments at locations where least soft-tissue artefacts were expected. For the pelvis, thigh, calf and foot segments these locations were, the sacrum, the iliotibial tract (about halfway between the hip and knee joint centres), the anterior-medial bony part of the tibia and the heel of the shoe, respectively (Figure 8-1). Kinematic and force plate data were low-pass filtered with a cut-off frequency of 5 Hz.



**Figure 8-1.** Left: photo of a subject performing a semi-squat technique. Right: stick figure illustrating how segment positions were obtained with the reference (position and orientation based) and orientation based methods. For the reference method, the ankle, knee, hip joint centres of the left leg and the L5/S1 joint centre were located using anatomical landmarks that were digitised in an upright reference posture using a probe with six markers (Cappozzo et al., 1995). The ankle joint centre was defined as the midpoint between medial and lateral malleoli, the knee joint centre was defined as the midpoint between the medial and lateral femur epicondyles and the L5/S1 and hip joint centres were estimated using the 3D positions of the left and right anterior and posterior superior iliac spines and regression equations from the literature (Reynolds et al., 1982; Bell et al., 1990). The L5/S1 joint centre was calculated with respect to the pelvis marker cluster. The other joint centres were calculated with respect to both the proximal and distal segment marker clusters. For moment calculation the following joint centres were used: the L5/S1 and hip joint centres attached to the pelvis marker cluster and the knee joint centre attached to the calf marker cluster. For the orientation based method, the foot position was the same as for the reference method. Starting at the ankle joint centre, the orientation based knee, hip and L5/S1 joint centres were calculated by linking the calf, thigh and pelvis segments using the orientation of each segment, in combination with a fixed segment length that was calculated from the distance between joint centres in the reference posture.

## Biomechanical analyses

Figure 8-1 explains how the positions of the relevant segments were obtained using the reference method that is frequently used in laboratory setting (based on the position and orientation of segments) and the orientation based method that can be applied when only information about the orientation of segments is available. Positions of the centres of mass and the moments of inertia were estimated according to Zatsiorsky (2002). For both methods, kinematics of the body segments were used together with the GRFs to calculate L5/S1, knee and hip moments in a bottom-up dynamic linked segment model (Kingma et al., 1996). To obtain the 3D components of the net moments (total, flexion & extension, ab- & ad-duction and endo- & exo-rotation moments), the knee moments were projected onto the calf coordinate system and hip and L5/S1 moments were projected onto the pelvis coordinate system. For the L5/S1 moment, symmetry between legs was assumed, so that only the extension component of the net moment remained. Note that for the reference method, the knee and hip joint centres were estimated with respect to both the proximal and distal segment marker clusters (Figure 8-1). Because the thigh cluster is most unstable (Garling et al., 2007), moments were calculated at the knee joint centre estimate from the calf marker cluster and at the hip joint centre estimate from the pelvis marker cluster. Ankle moments were not calculated, because the orientation based ankle joint centre position was the same as the reference ankle joint centre position (Figure 8-1). This would also be the case when measuring GRFs with an instrumented shoe, because then the ankle joint centre is fixed in the shoe coordinate system (Schepers et al., 2007).

## Statistical analyses

Because the differences between the moments obtained using the two methods were largest around lift-off (the instant the box was lifted by 1cm), the differences and absolute differences between methods in joint positions and moments were calculated at that instant in time. One-way repeated measures ANOVAs were

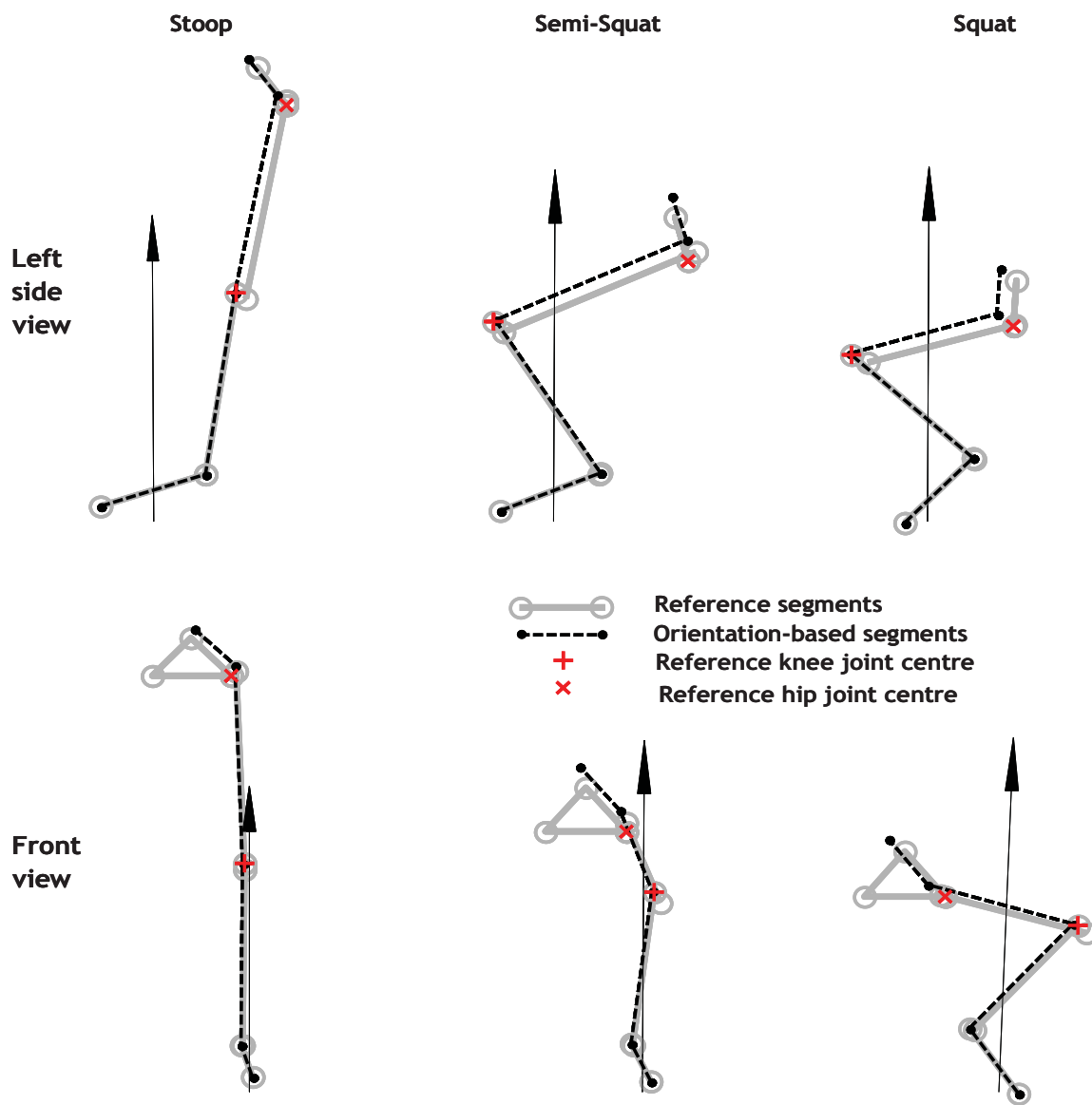
applied to test the effects of lifting technique on the differences and absolute differences. Subsequently, post-hoc LSD tests were applied in case of a significant effect of lifting technique. Additionally, for the differences (not for the absolute differences), student t-tests were performed to test if they significantly differed from zero, indicating systematic differences between the outcomes of the reference and orientation based methods.

## RESULTS

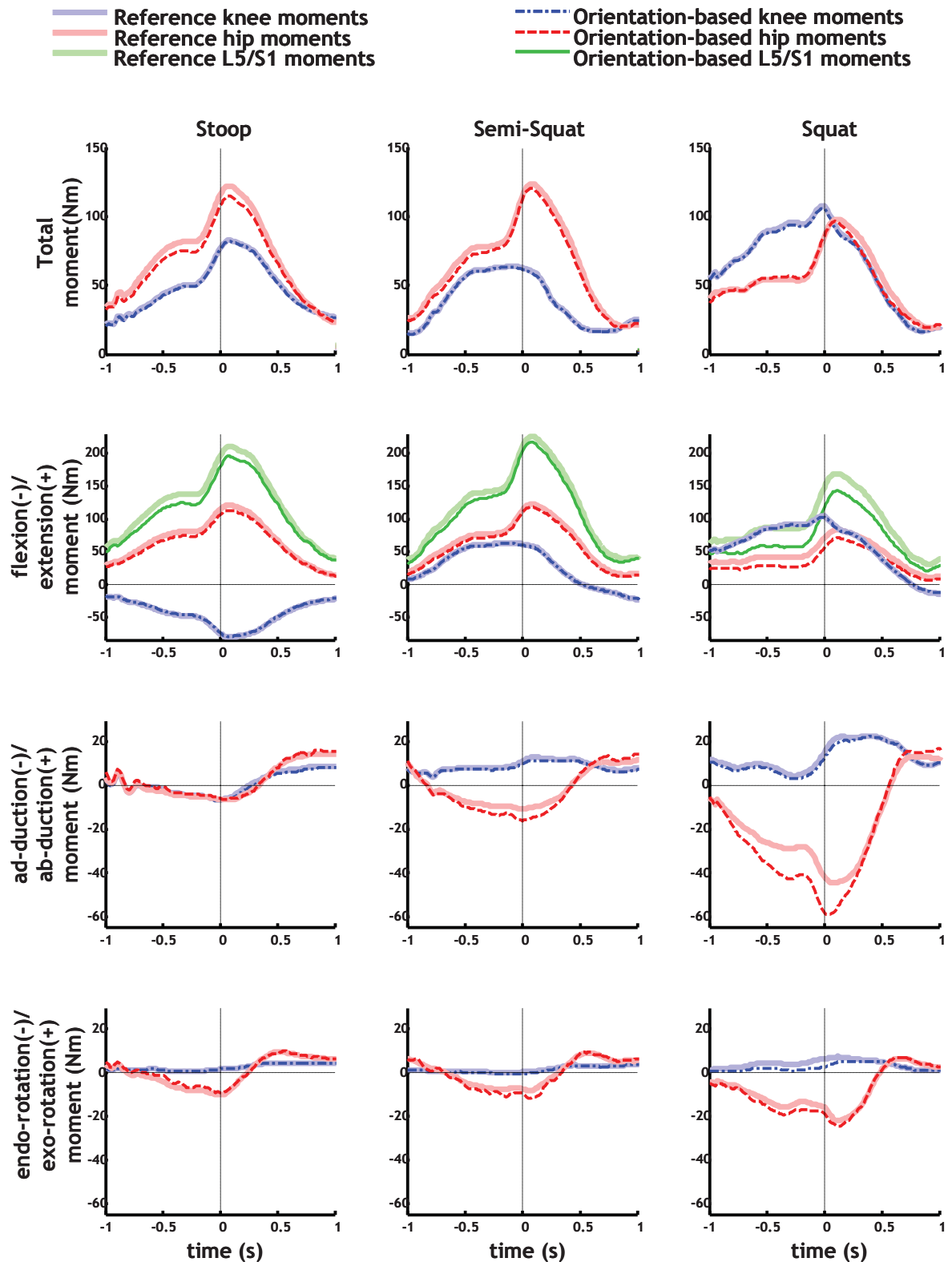
Figure 8-2 shows average stick figures at lift-off for the reference method and for the orientation based method. The differences and absolute differences in knee joint positions and moments between the reference method and orientation based method were generally small. Relative to the highest peak total moment, the moment differences and absolute differences remained below 2% for the stoop and semi-squat techniques and below 4% for the squat technique (Figure 8-3 and Table 1).

For the hip and L5/S1 joints, the position and moment differences and absolute differences were more substantial. Joint position differences and absolute differences in the horizontal plane (x- and y-direction) were largest for the squat technique, while in vertical direction (z-direction) they were largest for the semi-squat technique. Relative to the highest peak total moment, moment differences and absolute differences were up to 8% for the stoop and semi-squat techniques and up to 14% for the squat technique (Figure 8-3 and Table 8-1). In addition, in most cases the position and moment differences significantly deviated from zero, indicating systematic differences between methods.





**Figure 8-2.** Lower body stick figures at lift-off (pelvis and left thigh, calf and foot), averaged over subjects, for the reference method and the orientation based method. Note that for the reference method, joint centres were calculated with respect to both the proximal and distal segment (see also Figure 8-1) and that the knee joint centre attached to the calf segment and the hip joint centre attached to the pelvis segment were taken as reference joint centres for the comparison with the orientation based method. The arrow indicates the GRF beneath the left foot.



*Figure 8-3. Time series of the L5/S1, hip and knee moments, averaged over subjects, calculated using the reference method and the orientation based method. The vertical line in each plot indicate the instant in time that the differences between the two analysis methods were analysed (box lift-off).*

**Table 8-1.** Mean (SD) joint position and moment differences and absolute differences between reference method and orientation based method (orientation based - reference).

	Differences				Absolute differences			
	Technique effect (p-value)	Stoop (st)	Semi-Squat (ss)	Squat (sq)	Technique effect (p-value)	Stoop (st)	Semi-Squat (ss)	Squat (sq)
<b>Knee</b>								
x-direction	0.009	2(3) <sup>ss,z</sup>	-2(4) <sup>st,sq</sup>	3(6) <sup>ss</sup>	0.483	3(3)	3(3)	5(5)
y-direction	0.000	-2(4) <sup>sq</sup>	-3(4) <sup>sq,z</sup>	-9(6) <sup>st,ss,z</sup>	0.000	3(3) <sup>sq</sup>	5(3) <sup>sq</sup>	10(4) <sup>st,ss</sup>
z-direction	0.323	1(4)	2(3)	3(5)	0.470	2(3)	3(2)	4(4)
<b>Hip and L5/S1</b>								
x-direction	0.000	19(9) <sup>ss,sq,z</sup>	5(15) <sup>st,sq</sup>	33(18) <sup>st,ss,z</sup>	0.001	19(9) <sup>sq</sup>	13(7) <sup>sq</sup>	33(18) <sup>st,ss</sup>
y-direction	0.000	6(20) <sup>ss,sq</sup>	-13(22) <sup>st,sq</sup>	-35(27) <sup>st,ss,z</sup>	0.012	12(17) <sup>sq</sup>	22(12) <sup>sq</sup>	37(23) <sup>st,ss</sup>
z-direction	0.007	21(10) <sup>ss,z</sup>	48(23) <sup>st,sq,z</sup>	28(31) <sup>ss,z</sup>	0.004	21(10) <sup>ss</sup>	48(23) <sup>st,sq</sup>	33(25) <sup>ss</sup>
<b>Knee</b>								
total	0.180	-0.9(1.4)	-1.4(1.9) <sup>z</sup>	-2.1(1.7) <sup>z</sup>	0.065	1.1(1.3)	1.8(1.4)	2.3(1.4)
flexion-extension	0.001	1.0(1.4) <sup>ss,sq,z</sup>	-1.2(1.7) <sup>st,z</sup>	-1.5(1.9) <sup>st,z</sup>	0.148	1.2(1.2)	1.5(1.4)	2.1(1.0)
ab- ad-duction	0.001	-0.7(1.6) <sup>sq</sup>	-1.4(1.8) <sup>sq,z</sup>	-2.7(2.0) <sup>st,ss,z</sup>	0.002	1.2(1.2) <sup>sq</sup>	1.9(1.1) <sup>sq</sup>	3.0(1.4) <sup>st,ss</sup>
exto- endo-rotation	0.000	0.0(0.3) <sup>ss,sq</sup>	-0.9(1.1) <sup>st,sq,z</sup>	-3.8(3.1) <sup>st,ss,z</sup>	0.000	0.2(0.3) <sup>ss,sq</sup>	1.2(0.8) <sup>st,sq</sup>	4.3(2.4) <sup>st,ss</sup>
<b>Hip</b>								
total	0.000	-8.1(4.8) <sup>ss,sq,z</sup>	-2.7(6.3) <sup>st,sq</sup>	0.9(7.4) <sup>st,ss</sup>	0.236	8.2(4.5)	5.8(3.4)	5.7(4.5)
flexion-extension	0.000	-8.3(4.5) <sup>ss,sq,z</sup>	-3.5(5.7) <sup>st,sq</sup>	-15.5(8.5) <sup>st,ss,z</sup>	0.001	8.4(4.3) <sup>ss,sq</sup>	5.6(3.4) <sup>st,sq</sup>	15.5(8.5) <sup>st,ss</sup>
ab- ad-duction	0.000	0.7(3.4) <sup>ss,sq</sup>	-5.1(7.4) <sup>st,sq,z</sup>	-16.3(11.9) <sup>st,ss,z</sup>	0.000	2.4(2.3) <sup>ss,sq</sup>	7.5(4.7) <sup>st,sq</sup>	17.5(9.80) <sup>st,ss</sup>
exto- endo-rotation	0.049	1.0(5.0)	-2.2(5.0)	-2.9(3.7) <sup>z</sup>	0.574	3.3(3.7)	4.7(2.4)	3.6(3.0)
<b>L5/S1</b>								
flexion-extension	0.000	-16.7(9.50) <sup>ss,sq,z</sup>	-7.5(11.7) <sup>st,sq</sup>	-31.0(16.6) <sup>st,ss,z</sup>	0.001	17.3(8.2) <sup>ss,sq</sup>	11.5(7.4) <sup>st,sq</sup>	31.0(16.6) <sup>st,ss</sup>

<sup>st</sup>, <sup>ss</sup> and <sup>sq</sup> indicate that the difference significantly deviates from the difference found for the stoop (st), semi-squat (ss) and squat (sq) techniques, respectively. <sup>z</sup> indicates that the difference significantly deviates from zero (z) (tests not applied to the absolute differences)

## DISCUSSION

The present study investigated how accurate knee, hip and L5/S1 moments can be estimated, when only orientations of segments are available. For the knee moment, only small differences with the reference method were found, which can be explained by the small differences between the ankle joint centre positions estimated from foot and calf coordinate systems (Figure 8-2). Because the orientation based hip and L5/S1 positions and moments were not only affected by position differences in the ankle joint centre, but also by the position differences in the knee and hip joint centres, position and moment differences were substantially larger than for the knee joint. As expected, especially the squat technique resulted in high moment differences due to relatively large position differences in the horizontal plane. The semi-squat technique resulted in the largest position difference in the vertical direction, but because the horizontal component of GRF was small, this barely affected the moments. Large position errors may be prevented in future ambulatory measurement systems by incorporating a recently developed body mounted system that can track positions of IMSs with reasonable accuracy (Roetenberg et al., 2007; Schepers et al., 2010).

### Limitations

Some limitations of the present study should be mentioned. First, the orientations of cluster markers were used instead of the orientations of IMSs because the aim of the present study was to test the differences between the outcomes of the two analysis methods (orientation based vs. orientation and position based), while assuming accurate orientation measurement. When measuring with actual IMSs, the orientation around the vertical axis can contain substantial errors, especially near ferromagnetic materials such as a force plate (Roetenberg et al., 2005; de Vries et al., 2009). Furthermore, it should be noted that when using an IMS instead of an optoelectronic system, the current position based anatomical calibration procedure is not suitable, so that a different method is required to relate the IMS coordinate systems with the anatomical systems of the segments (O'Donovan et al., 2007; Picerno et al., 2008; Favre et al., 2009; Cutti et al., 2010). Second, the use of orientation based systems heavily depends on accurate determination of

the position of joint centres in the anatomical coordinate systems. Better estimates of joint centres might improve accuracy. As we expected a substantial joint centre location error in the hip, we tried an alternative hip joint centre calculation in which leg length is used as additional input (Leardini et al., 1999), but this increased rather than reduced resulting differences in hip and L5/S1 moments. Third, the present study only investigated lifting tasks, in which vertical position differences do not affect the moments much. Other tasks involving larger horizontal GRFs (e.g. pushing and pulling) might be more sensitive to these vertical position differences. Finally, it should be noted that the subjects were mainly young lean males and that errors due to soft-tissue artefacts may be larger in other groups (e.g. women and obese people).

## **CONCLUSION**

The present study showed that bottom-up calculated knee moments could be estimated with good accuracy during manual lifting when using only the orientation instead of the orientation and position of segments. Hip and L5/S1 moments could be estimated with less accuracy, especially when subjects used a squat technique.

## **ACKNOWLEDGEMENTS**

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