Supplemental digital content 1: marker based PCA to assess global compensation strategies

To assess global compensation strategies, we performed Principal Component Analysis (PCA) on the marker data. This technique has been used previously to decompose movements in different principal components (PC’s) that each represent distinct movement strategies or principal movements (PM’s). Marker data were normalized and scaled based on previously described methods before the PCA was performed. PM’s were then calculated for each task separately. A detailed overview of all steps and results can be found below.

1. Methods
1.1 Marker selection + filtering:
We used the ‘Liverpool John Moores University’ marker model (44 markers) in this study. We only selected those markers that were positioned on well-defined anatomical landmarks and did not contain excessive gaps in marker trajectories for the PCA analysis. The following markers were retained:

- Heel left + right
- Metatarsal head (MTH) 1 left + right
- MTH5 left + right
- Malleolus lateralis left + right
- Lateral knee left + right
- Functional hip left + right
- Posterior superior iliac spine (PSIS) left + right
- Acromion left + right
- T8

The marker trajectories were all filtered with a 4th order lowpass Butterworth filter with a cut-off frequency of 18 Hz before further analyses were performed.

Based on the three-dimensional coordinates of all markers, a posture vector could be created for every subject and every trial at a given time $t$. This posture vector could be created according to the following formula:

$$ p(t) = [x_1(t), y_1(t), z_1(t), ..., x_j(t), y_j(t), z_j(t)] $$

- with $p$ being the posture vector at time $t$
- $x,y,z$ are the marker coordinates of the respective marker
- $j$ is number of markers (17 in this study)

1.2 Normalization:
To allow for comparison between subjects, we applied a normalization procedure on the posture vectors, based on previously described methods.

The aim of this normalization procedure is to ensure that:

1. all subjects contribute equally in the PCA
2. anthropometric differences between subjects are minimized
3. the relative amplitude of the marker motion is preserved
4. the fraction of body weight that each marker represents is adequately scaled

**Step 1: subtracting mean posture vector of each posture vector to create postural movement vector**

For every subject and for every trial we calculated a mean posture vector that represents the mean position of every marker during that specific trial.

\[
p_{\text{subj,trial}} = [x_1, y_1, z_1, ..., x_{17}, y_{17}, z_{17}]\]

Subsequently this mean posture vector was subtracted from the respective posture vector. The new posture vector \((p')\) represents thus the deviations from a subject’s mean posture or the postural movements for that specific trial.

\[
p'_{\text{subj,trial}}(t) = p_{\text{subj,trial}}(t) - p_{\text{subj,trial}}\]

**Step 2: subtracting Euclidean norm of each postural movement vector**

To remove anthropometric differences between subjects, we divided the postural movement vector by the mean Euclidean norm of each subject.

The Euclidean norm is calculated as follows:

\[
d_{\text{subj}} = \|p'_{\text{subj,trial}}(t)\|_2\]

Division of postural movement vector by Euclidean norm:

\[
p''_{\text{subj,trial}}(t) = \frac{p'_{\text{subj,trial}}(t)}{d_{\text{subj}}}\]

**Step 3: Marker weighting and calculation of scaling matrix**

In the last step the marker coordinates were multiplied by a weighting factor to take into account the relative mass of all segments and the amount of markers that were attached to the segment. The weight factor \(w\) was calculated by dividing the relative mass of the segment (based on De Leva et al.) by the number of markers attached to that segment. For markers that were placed on joints, the masses of both segments were added.

\[
w_{\text{heel left}} = \frac{\text{Relative mass left foot}}{\text{number of markers on left foot}} = \frac{1.37\%}{3}\]

A scaling matrix was calculated to reverse the normalization in a later step (1.5 visualization of PM’s). The scaling matrix was calculated by dividing the Euclidean norm by the weighting matrix \((W)\) that contains the marker weightings.

\[
S = \frac{d_{\text{subj}}}{W}\]

**1.3 Pooling of data**

We concatenated the normalized postural movement vectors of all subjects in one large matrix \(M\). This was performed for every task separately, leading to 5 pooled matrices \(M\).
The matrix M contains 12852 rows and 51 columns.

- The rows represent: trials (each participant performed 3 trials on each leg (42 participants*2legs*3trials)) * trial duration (500 msec) * sample frequency (100Hz)
- The columns represent: amount of markers (17)* coordinates (3)

1.4 PCA
After the normalization steps and the data pooling, a PCA was run on the pooled matrix M to calculate the following results:

1. $v_k$ = Eigenvectors: represent the direction of the most variability in the data, with the amount of variability strictly decreasing with increasing $k$.
2. $ev_k$ Eigenvalues: describe the amount of variance explained by the eigenvector.
3. $\xi$ = time evolution coefficients/PC-scores: describe the loading (level of expression) of each PC.

1.5 Assessment of differences in loading of PM’s between groups
To assess alteration in whole body landing strategies between 1) the injured and uninjured leg of the ACL group and (2) the ACL injured leg and the control group, we assessed which PM’s were expressed more or less in a certain group compared to another group by comparing time evolution coefficients ($\xi$).

Paired SPM1D t-tests were used to compare the time evolution coefficients between the injured legs and the uninjured legs of the ACL group, Unpaired SPM1D t-tests to assess differences in expression between the ACL injured legs and the control group.

We decided to only retain PM’s that met the following criteria:

- Significant difference in time evolution coefficients between groups (p<0.05)
- A Cohen’s effect size >0.51
- The significant difference between groups was based on amplitude-differences. We decided to no include timing-differences as our tasks were not cyclic and thus do not represent a well-defined period (for every subject IC was used as starting point and 500msec post IC as end point). Differences in task execution speed could thus be confused with timing differences.

We limited the analyses to the first 15 PM’s as these PM’s explained most of the variance (>99.5%).

1.5.1 Time evolution curves
Below the time evolution plots of all tasks can be found.
Figure A1.1: Row 1-4-7: average time evolution coefficients of the control group (black line), the ACL injured leg group (red line) and the ACL uninjured leg group (blue line) for the first 15 PM’s during the landing phase of the single leg hop for distance (from IC until 500ms post IC). Standard deviation clouds are represented by the shaded zones. Row 2-3-5-6-8-9: output of SPM t-tests (unpaired/paired): if the t-curve (black line) exceeds the critical threshold (horizontal red dashed line) a significant difference in expression of that PM exists.
Figure A1.2: Row 1-4-7: average time evolution coefficients of the control group (black line), the ACL injured leg group (red line) and the ACL uninjured leg group (blue line) for the first 15 PM’s during the landing phase of the medial hop (from IC until 500ms post IC). Standard deviation clouds are represented by the shaded zones. Row 2-3-5-6-8-9: output of SPM t-tests (unpaired/paired): if the t-curve (black line) exceeds the critical threshold (horizontal red dashed line) a significant difference in expression of that PM exists.
Figure A1.3: Row 1-4-7: average time evolution coefficients of the control group (black line), the ACL injured leg group (red line) and the ACL uninjured leg group (blue line) for the first 15 PM’s during the landing phase of the lateral hop (from IC until 500ms post IC). Standard deviation clouds are represented by the shaded zones. Row 2-3-5-6-8-9: output of SPM t-tests (unpaired/paired): if the t-curve (black line) exceeds the critical threshold (horizontal red dashed line) a significant difference in expression of that PM exists.
Figure A1.4: Row 1-4-7: average time evolution coefficients of the control group (black line), the ACL injured leg group (red line) and the ACL uninjured leg group (blue line) for the first 15 PM’s during the landing phase of the vertical hop with 90° medial rotation (from IC until 500ms post IC). Standard deviation clouds are represented by the shaded zones. Row 2-3-5-6-8-9: output of SPM t-tests (unpaired/paired): if the t-curve (black line) exceeds the critical threshold (horizontal red dashed line) a significant difference in expression of that PM exists.
Figure A1.5: Row 1-4-7: average time evolution coefficients of the control group (black line), the ACL injured leg group (red line) and the ACL uninjured leg group (blue line) for the first 15 PM’s during the landing phase of the vertical hop with 90° lateral rotation (from IC until 500ms post IC). Standard deviation clouds are represented by the shaded zones. Row 2-3-5-6-8-9: output of SPM t-tests (unpaired/paired): if the t-curve (black line) exceeds the critical threshold (horizontal red dashed line) a significant difference in expression of that PM exists.
### 1.5.2 Overview of retained PM’s

**A) Single leg hop for distance**

1. ACL injured vs control (unpaired t-test): no significant differences
2. ACL injured vs uninjured (paired t-test)

<table>
<thead>
<tr>
<th>PM</th>
<th>Criteria 1 p-value</th>
<th>Criteria 2 ES</th>
<th>Criteria 3 Amplitude difference?</th>
<th>Retained?</th>
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<tbody>
<tr>
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<tr>
<td>9</td>
<td>&lt;0.001 &amp; 0.008</td>
<td>0.45 &amp; -0.45</td>
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<tr>
<td>12</td>
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</table>

**B) Vertical hop with 90° medial rotation**

1. ACL injured vs control (unpaired t-test)

<table>
<thead>
<tr>
<th>PM</th>
<th>Criteria 1 p-value</th>
<th>Criteria 2 ES</th>
<th>Criteria 3 Amplitude difference?</th>
<th>Retained?</th>
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</thead>
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2. ACL injured vs uninjured (paired t-test): no significant differences

**C) Vertical hop with 90° of lateral rotation**

1. ACL injured vs control (unpaired t-test)

<table>
<thead>
<tr>
<th>PM</th>
<th>Criteria 1 p-value</th>
<th>Criteria 2 ES</th>
<th>Criteria 3 Amplitude difference?</th>
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2. ACL injured vs uninjured (paired-test)

<table>
<thead>
<tr>
<th>PM</th>
<th>Criteria 1 p-value</th>
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<th>Criteria 3 Amplitude difference?</th>
<th>Retained?</th>
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D. Medial hop  
1. ACL injured vs control (unpaired t-test)

<table>
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<th>PM</th>
<th>Criteria 1 p-value</th>
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2. ACL injured vs uninjured (paired t-test)

<table>
<thead>
<tr>
<th>PM</th>
<th>Criteria 1 p-value</th>
<th>Criteria 2 ES</th>
<th>Criteria 3 Amplitude difference?</th>
<th>Retained?</th>
</tr>
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<td>-0.37 &amp; 0.46</td>
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<tr>
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<td>0.0416</td>
<td>0.40</td>
<td></td>
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</tr>
</tbody>
</table>

E. Lateral hop  
1. ACL injured vs control (unpaired t-test) no significant differences  
2. ACL injured vs uninjured (paired t-test) no significant differences

1.6 Visualization of retained PM’s
To visualize the differences in landing strategies between groups, we created overlying stick figures. To create the stick figures, the retained PM was ‘transplanted’ in the mean posture vector of the control group. Marker positions were calculated as follows:

\[
\begin{align*}
\hat{p}_{\text{controls}}^k &= p_{\text{controls}} + a \ast S_{\text{controls}} \ast \xi_{\text{controls}} \ast v_k \\
\hat{p}_{\text{ACL injured}}^k &= p_{\text{controls}} + a \ast S_{\text{controls}} \ast \xi_{\text{ACL injured}} \ast v_k
\end{align*}
\]

This approach makes it possible to visualize how the movement pattern of a group changes when only one PM is altered. An amplification factor (a) was used to better visualize differences. The amplification factor is always noted down in the figures.

1.7 Naming of PM
Finally, a relevant name was given to the PC’s based on visual inspection. As the PM’s represent ‘movements’ and not postures, stick figures were created at every time frame and subsequently plotted for an animated visual appraisal of how each PM evolved over time. Two independent investigators assessed the animations to ensure that the PM’s were labelled correctly.