length of seven samples and a polynomial order of two. These values were found to provide an optimal combination of precision and smoothness in the time derivatives.

E. Mechanical energy

For the estimation of kinetic variables, we used the body segment model proposed by Dempster (Robertson, Caldwell, Hamill, Kamen, & Whittlesley, 2004). The model specifies a number of parameters for each of the body segments. These are the mass of the segment in relation to the total body mass, the distance of the center of mass from the proximal joint in relation to the segment length, and the radius of gyration in relation to segment length with respect to the center of mass, the proximal joint, and the distal joint.

As a first step in the kinetic analysis, we estimated the total instantaneous potential and kinetic energy of the body, averaged across participants and across 4-beat segments in the stimuli. The average energies are shown in Fig. 2. As can be seen, the average potential energy displays a clear periodicity at the one-beat level, the beat location closely matching with the point of maximal decrease in potential energy and thus maximal downward velocity of the body. Average kinetic energy, on the other hand, displays a clear superposition of half-beat and two-beat periods.

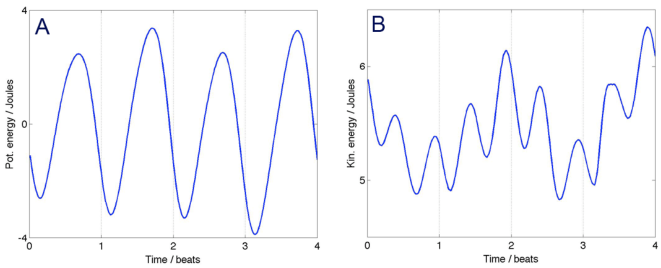

Fig. 2. Total potential (A) and kinetic (B) energy of the body, averaged across participants and 4-beat segments.

Subsequently, we performed a more detailed periodicity analysis of the components of mechanical energy. To this end, we estimated the period of potential and kinetic energy in each 4-beat segment of the data using autocorrelation, and estimated the period distribution using kernel density estimation. Fig. 3 displays the distribution of periods for potential energy. As can be seen, the most common periodicity for most tempi corresponds to the length of one beat, with a two-beat period being the second most prominent. An exception is the tempo 92 BPM, for which the two-beat period is the most prominent.

Fig. 4 shows the distribution of estimated period for kinetic energy. In this case, the most common periodicity for each tempo corresponds to the length of two beats, while four-beat periods are also relatively common.

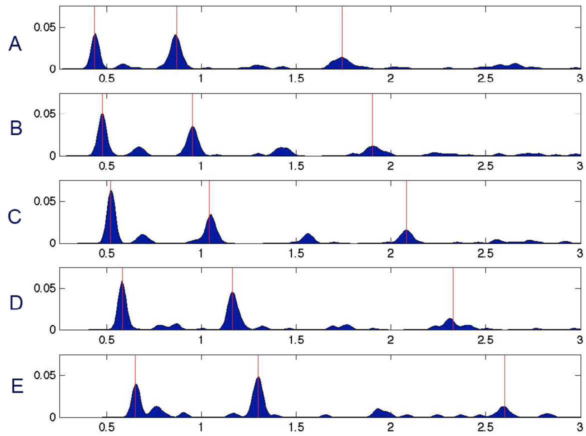

Fig. 3. Distribution of periodicities for potential energy for each of the five tempi. A. 138 BPM; B. 126 BPM; C. 115 BPM; D. 103 BPM; E. 92 BPM. In each subplot, the vertical lines display the length of one, two, and four beats in the stimulus.

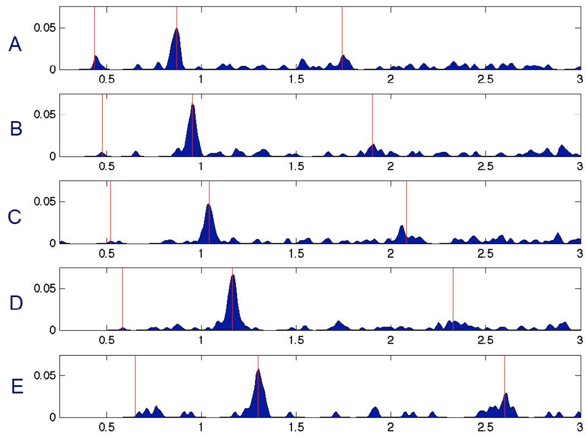

Fig. 4. Distribution of periodicities for kinetic energy for each of the five tempi. A. 138 BPM; B. 126 BPM; C. 115 BPM; D. 103 BPM; E. 92 BPM. In each subplot, the vertical lines display the length of one, two, and four beats in the stimulus.

F. Eigenmovements

Next, we extracted typical movement patterns from the data and investigated their periodicities. To this end, the data was decomposed into 8-beat sections with 50% overlap between neighbouring sections. This decomposition was carried out because many of the participants changed their movement patterns during presentation of the stimuli. The decomposition resulted in 55 sections for each participant (11 sections for each tempo). Subsequently, a Principal Components Analysis (PCA) was carried out separately for each participant and each section.

The first three Principal Component projections from each PCA were subjected to a periodicity analysis using autocorrelation. Using a tolerance of 10%, we found that that 4% of the Principal Components were synchronized with the one-beat level, while 16% and 20% were synchronized with the two-beat and four-beat levels, respectively. The rest of the

Principal Component projections either had another period or were aperiodic.

To investigate the prevalence of different movement patterns on various metrical levels, a second (between-subjects) PCA was carried out on the eigenmovements (i.e., Principal Components obtained from the first PCA) that were synchronized with one of the three metrical levels (one, two, or four beats).

As a general remark, we observed differences between the three metrical levels in terms of the distribution of the secondary PC projections. In a more detailed analysis, we detected the most typical movements for each of the three metrical levels by identifying the synchronized eigenmovements whose PC projections displayed the highest variance. This analysis suggested the following most typical eigenmovements for each of the metrical levels.

- One-beat level: (1) mediolateral arm movements; (2) vertical hand and torso movements;
- Two-beat level: (1) mediolateral arm movements; (2) rotation of the upper torso;
- Four-beat level: (1) lateral flexion of the body; (2) rotation of the upper torso.

Fig. 5 displays these eigenmovements schematically[1].

IV. DISCUSSION

We investigated spontaneous movement to music, with a special emphasis on the relationship between movement patterns and metrical levels of music. A kinetic analysis of the movement data revealed that the average potential energy displayed a period of one beat, with the location of the beat closely corresponding to the point of maximal instantaneous decrease of potential energy and thus maximal overall downward velocity of the body. The kinetic energy, on the other hand, displayed a superposition of periods of half a beat and two beats. A more detailed analysis of periodicities in the different forms of mechanical energy of the body showed that the most common periods for potential energy were one and two musical beats, while those for kinetic energy were two and four beats. These observations suggest that the various metrical levels of the musical stimulus were embodied as different forms of mechanical energy.

Subsequently, we performed a two-stage Principal Components Analysis and periodicity analysis on the movement data in order to find typical movement patterns that were synchronized with each of the three main metrical levels of the musical stimulus. The results of this analysis revealed differences in terms of the prevalence of eigenmovements between the different metrical levels. In particular, the tactus level was associated with mediolateral arm movements as well as vertical hand and torso movements, the two-beat level with mediolateral arm movements and rotation of the upper torso, and the four-beat level with lateral flexion of the torso and rotation of the upper torso.

The results imply that periodicities on several metric levels are simultaneously present in spontaneous movement to music. This could suggest that the metric structure of music is encoded in such spontaneous movements.

[1] An animation of the eigenmovements is available on the internet at http://dl.getdropbox.com/u/567596/eigenmovements.mov

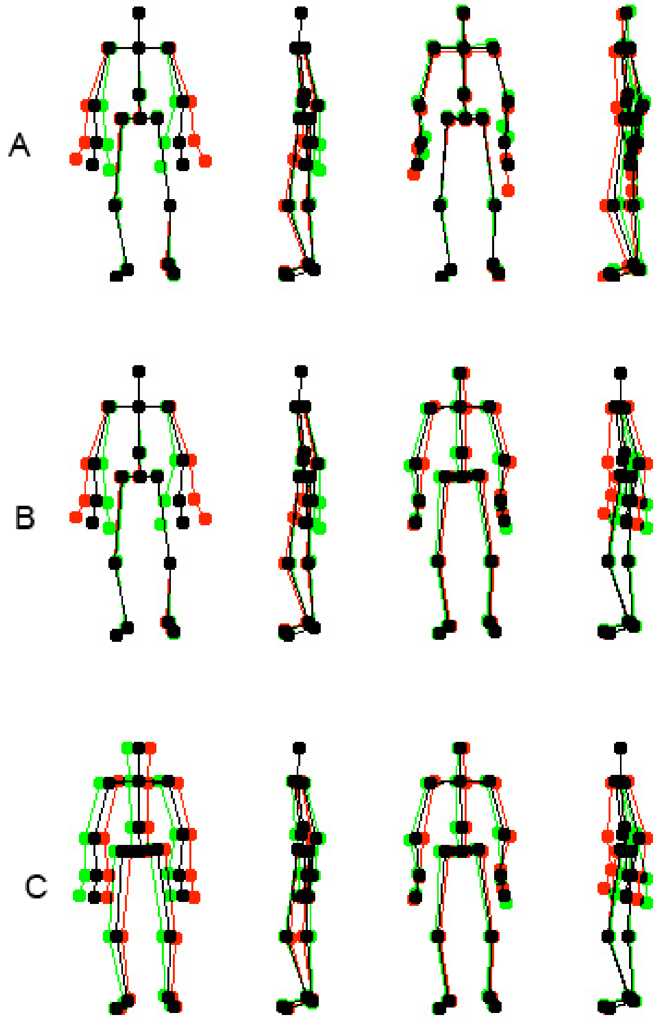

Fig. 5. Typical eigenmovements for periods of (A) one beat; (B) two beats; (C) four beats. Each eigenmovement is displayed with both a frontal and a lateral view. The mean posture of the eigenmovement is displayed in black, while the points with maximal deviation from the mean posture are displayed in red and green.

ACKNOWLEDGMENTS

We thank Aki Tulikari for his help in collecting the motion-capture data. This study was supported by the Academy of Finland (projects 125710, 110576, and 119959).

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