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# Effects of movement for estimating the hip joint centre

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## Abstract

Determination of the hip joint centre (HJC) using a functional approach requires access to the kinematics of various body postures. The present study aimed to determine the combined impact of the nature of the movement, its type and the number of cycles, on the accuracy of HJC estimation.

Kinematics noise was modelled based on the deformation of hip and thigh clusters of seven subjects, while perfect ball-and-socket movements (used as reference) were calculated based on the movements of one of the subjects. The noise added to the reference kinematics allowed the simulation of 27 tests. Errors were defined as the Euclidean distance between the estimated and the reference HJC. A nested ANOVA and a multiple comparison procedures were performed on all errors.

A test including 10 cycles of three different types of limited movements (flexion-extension, abduction–adduction and circumduction) yielded the greatest accuracy for estimating HJC (4.0 ± 1.3 mm). Combining different types of movements allowed improving the accuracy. Given that noise increases as a function of the range of a motion, limited movements proved to be the most accurate; however, 10 cycles were required to achieve such results. For trials involving a single cycle, a large movement proved more efficient.

*Keywords:* Hip joint centre; Simulation; Movement; Functional method; Noise

## 1. Introduction

The analysis of the joint forces and moments underlying human movements has typically been based on inverse dynamics. Poor estimations of the joint centre locations have led to the distortion of computed angles and moments. Errors of 20–30 mm in hip joint centre (HJC) location may lead to substantial inaccuracies in hip moment calculations [1,2]. HJC, modelled as a ball-and-socket joint, can be estimated using either a functional or a predictive approach [3]. Each approach carries its own inconveniences. Three different sources of error may affect HJC prediction: marker location, regression uncertainty, and anthropometric measurement. In addition, only relatively small sample sizes of living adults or cadaver specimens have been used. In the functional approach, the kinematics of external markers is affected by the presence of noise. The movements of the soft tissues add to the displacements of the underlying bone structure. Previous studies [4–6] have reported skin movement values of up to 40 mm. The largest deviations were found on skin portions close to joints and were related to changes in the joint angle.

Several attempts have been made to compare the predictive and functional approaches [1,7,8]. The main problem for such comparison is the lack of a standard functional method, as there are many different algorithms, and movement characteristics differ from one study to the other. The main differences concern the nature of movement (range of motion and velocity), its type (i.e. flexion-extension, abduction–adduction and circumduction) and the number of cycles taken into account. HJC estimation requires the analysis of several postures that depend on these three characteristics. The compromise between various postures and noise is complex.

With computer-based simulation or mechanical linkage, the exact location of the joint centre is known. The characteristics of the movement can be easily changed in order to measure their effect. Numerical simulation offers

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the advantage of including a model of noise applied to controlled kinematics. The purpose of this paper was to evaluate the effects and interactions of three movement characteristics on HJC estimation. The HJC was estimated using a functional approach based on simulated movements that integrated the noise induced by skin movements.

## 2. Materials and methods

The present study used the functional method proposed by Gamage and Lasenby [9] and modified by Halvorsen [10]. A *Saga*$3^{RT}$ motion analysis system (Biogesta, Valenciennes; France) was used to collect kinematical data with six infrared cameras (50 Hz) inside a calibrated volume of 2 m × 1 m × 1 m.

### 2.1. Experimental design

Seven healthy male gymnasts ($21 \pm 2.7$ years old; $1.71 \pm 0.04$ m; $71.3 \pm 5.4$ kg) participated in this study after having given their informed consent. Two clusters of three non-colinear markers (20 mm diameter spherical balls) were placed on the pelvis and on the right thigh, as far as possible from the hip joint and large muscles (Fig. 1). An anatomic calibration [11] of the femoral epicondyles was performed.

While maintaining their trunk vertical, the subjects were required to perform three types of right thigh movements composed of 10 cycles: flexion-extension (FE), abduction–adduction (AbAd) and circumduction (Cir). These movements were repeated three times with different velocities and ranges of motion. In the first trial, subjects were instructed to limit the range of motion, thereby minimising contraction of the superficial muscles of the thigh. The second trial consisted in performing slow movements with maximum amplitude. The third trial involved maximal explosive movements. These different natures of movement were noted as: limited, full and explosive, respectively.

### 2.2. Reference kinematics: rigid segments and a unique HJC location

In order to obtain realistic cluster trajectories, reference movements were simulated using the experimental movements of one of the subjects. After eliminating the most distorted clusters[1], these were solidified using a least squares minimisation method [12]. The elimination of clusters was not an issue for estimating HJC as the functional approach used is independent of time. Based on this data, a reference HJC location was determined, and the eliminated clusters were then interpolated so as to obtain a reference kinematics with rigid segments and a unique HJC location[2]. The coordinates were close to the experimental movement. They included 10 cycles of each nature and type of movement.

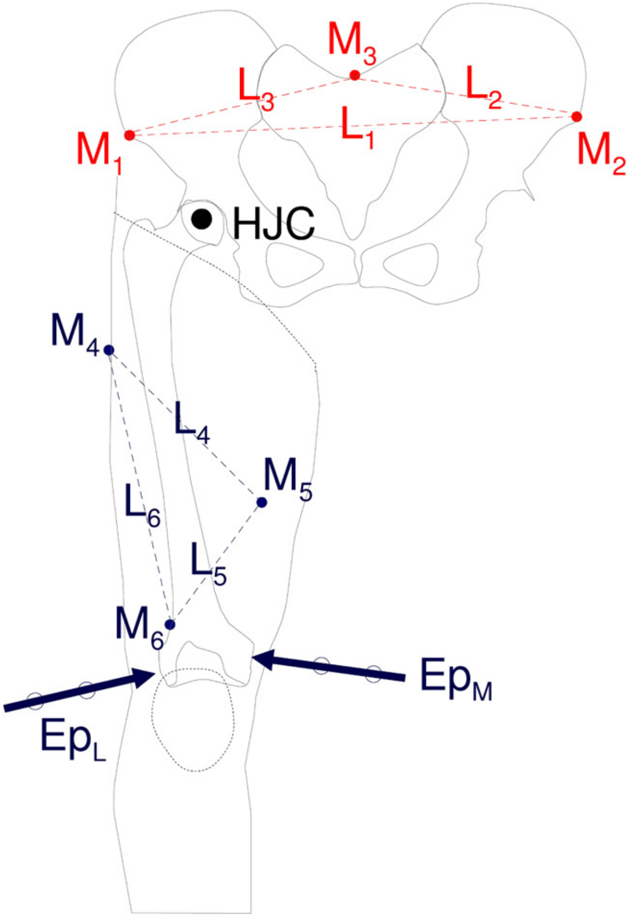

Fig. 1. Six technical markers ($M_j$), defining the six lengths ($L_j$), were placed on the skin in order to define the position and orientation of the pelvis and thigh: $M_1$, left anterosuperior iliac spine (ASIS); $M_2$, right ASIS; $M_3$, sacrum; $M_4$, on the lateral side of the thigh, approximately 0.1 m under the greater trochanter; $M_5$, on the medial side of the thigh, between the vastus medialis and the rectus femoris; $M_6$, on the vastus lateralis tendon. Lateral and medial epicondyles ($\mathrm{Ep_L}$, $\mathrm{Ep_M}$) were calibrated during a static posture phase.

### 2.3. Noise model

Noise was added to the reference kinematics. The artificial noise included random and continuous components, and was designed to account for artefact skin movements and measurement errors. The model is based on the hypothesis that the changes in cluster dimensions provide an indication as to the skin movement artefact. The length deformation between markers of both clusters was calculated for each cycle and for the seven subjects. An average deformation was determined for each nature of movement and each length. Since cluster deformation presented a cyclic behaviour with the largest deviations observed near the maximal flexion or abduction, a Gaussian curve was used to define the continuous component of the noise (see Fig. 2). Moreover, a random noise component was

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[1] Details in Appendix A.1.

[2] Details in Appendix A.2.

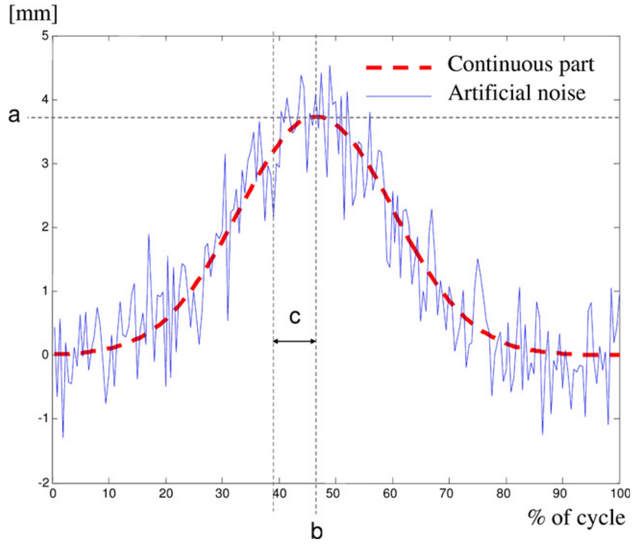

Fig. 2. The artificial noise included continuous and random components. Continuous noise for one cycle was computed as a Gaussian curve with amplitude *a*, mean *b*, and standard deviation *c*. The continuous component was repeated throughout the trial on the marker coordinates.

added to account for the measurement error of the stereophotogrammetric system. To summarise[3], there were five random parameters and 18 coefficients $a2_{j,k}$, one for each of the six markers and for each of the three natures of movement. When added to the reference kinematics the noise was equivalent, on average, to the experimental deformation of the clusters.

### 2.4. Computer modelling

One nature, one type of movement and one number of cycles were chosen successively with three modalities:

(1) nature of movement {limited, full, explosive},
(2) type of movement {FE/AbAd, Cir, FE/AbAd/Cir}, and
(3) number of cycles {1, 5, 10}.

The combination of these three characteristics resulted in 27 different tests. The cycles necessary for each test were extracted from the reference kinematics and were combined with an artificial noise pattern. The random parameters of the noise model allowed the simulation of different patterns. Numerical simulations were performed using Matlab 6.5 (PC, Pentium 4, 2.5 GHz). The HJC location was estimated for each noise pattern and each test. Errors were considered to correspond to the Euclidean distance between estimated and reference HJC locations. A nested ANOVA was performed on all test errors. When a significance level of $p \leq 0.01$ was evidenced, a multiple comparison procedure, using Tukey's method, was performed in order to further investigate the differences between modalities.

Table 1
Hip joint range of motion (angles in degrees) for the three types of nature of movement

| | AbAd | | | FE | | |
|---|---|---|---|---|---|---|
| | Minimum | Maximum | Range | Minimum | Maximum | Range |
| Limited | – 5 | 53 | 58 | – 28 | 46 | 74 |
| Full | – 9 | 77 | 86 | – 39 | 60 | 99 |
| Explosive | – 7 | 94 | 101 | – 27 | 91 | 117 |
| Ref. [8] | | | 40 | | | 45 |
| Ref. [13] | | | 29.4 | | | 60.4 |

Values reported in previous studies are shown for comparison purposes.

## 3. Results

### 3.1. Reference kinematics and noise

The thigh segment was defined by the HJC and the middle of the femoral epicondyles (Fig. 1). The hip range of motion was measured in the sagittal plane of the pelvis for FE and in the frontal plane for AbAd (Table 1). The range of the limited motion (58° in AbAd and 75° in FE) was greater than what has been used in previous studies [8,13].

Due to the random parameters of the noise model, 500 generations of noise pattern were necessary in order to achieve convergence of the average cluster deformation value. The respective average length deformations observed for the limited, full, and explosive movements were 2.9 mm (2.2 mm for the hip versus 3.6 mm for the thigh), 4.5 mm (3.6 versus 5.5) and 5.1 mm (4.5 versus 5.8). Except for marker $M_4$ (see Fig. 1), the systematic error increased according to the range of the motion. In addition, the noise observed on the pelvis cluster was lower than on the thigh. A maximum displacement of 15 mm was observed for $M_4$ during the explosive movement, this was approximately 13 mm for $M_5$ and $M_6$.

### 3.2. Effects of the movement characteristics

Table 2 shows the average error in HJC estimation and standard deviation for all tests. The highest accuracy test (4.0 mm) comprised of 10 cycles of limited FE/AbAd/Cir

Table 2
Average errors (and standard deviation) for each test: combination of nature, type of movement and number of cycles

| Natures | Number of cycles | Types | | |
|---|---|---|---|---|
| | | FE/AbAd | Cir | FE/AbAd/Cir |
| Limited | 1 | 7.9 (2.5) | 5.0 (1.5) | 4.9 (1.6) |
| | 5 | 6.2 (2.1) | 4.8 (1.3) | 4.5 (1.5) |
| | 10 | 5.5 (1.9) | 4.5 (1.2) | 4.0 (1.3) |
| Full | 1 | 6.7 (2.3) | 5.8 (1.9) | 4.7 (1.4) |
| | 5 | 6.7 (2.1) | 5.7 (1.6) | 4.6 (1.4) |
| | 10 | 6.5 (2.1) | 5.7 (1.5) | 4.6 (1.4) |
| Explosive | 1 | 6.1 (2.0) | 6.7 (2.1) | 4.8 (1.6) |
| | 5 | 5.7 (1.9) | 6.5 (2.3) | 4.6 (1.7) |
| | 10 | 5.7 (1.9) | 6.5 (2.3) | 4.5 (1.6) |

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[3] The model is fully developed in Appendix (A.3).

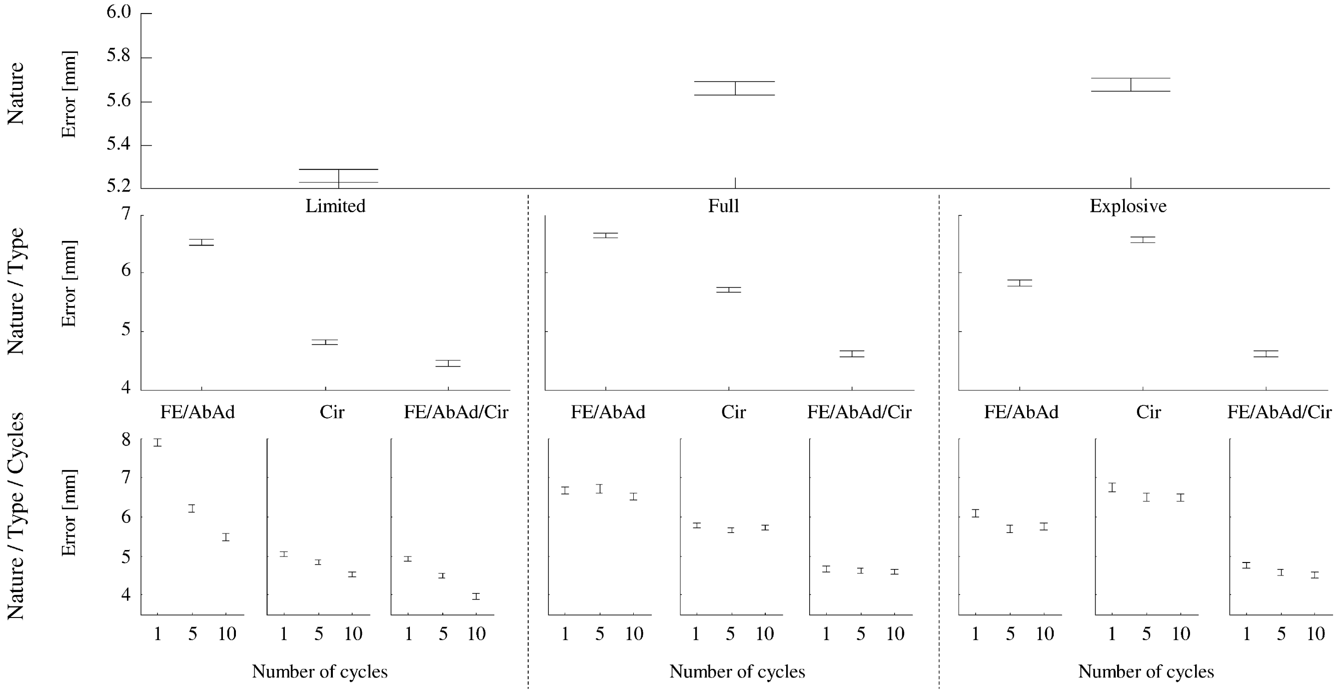

Fig. 3. Graphical representation of the multiple comparison procedure of the nested ANOVA. The standard error of the estimated means was calculated using Tukey's post hoc test. The nature of the movement, the nature–type interactions and the nature–type–cycles interactions were tested successively. Two means were considered to be significantly different when their intervals did not overlap, and were considered as not differing significantly when their intervals overlapped ($p < 0.01$).

movements. The lowest accuracy test (7.9 mm) was obtained with one cycle of limited FE/AbAd. Since the nested ANOVA revealed significant differences ($p < 0.001$), multiple comparison procedures were performed.

The statistical results are presented in Fig. 3. The nature of the movements had a significant effect on the accuracy of HJC estimation. The limited movements were more accurate than full or explosive movements. The type of movement presented interactions with the nature, with the effect differing according to the three natures of movements. Overall, FE/AbAd/Cir was significantly the most accurate. For limited or full movements, the accuracy increased between FE/AbAd, Cir and FE/AbAd/Cir. For explosive movements, Cir yielded the lowest accuracy. The number of cycles had no significant effect in any of the nature–type interactions, modifications were only related to the nature of the movement. For limited movements, the accuracy increased with the number of cycles. For the full range of motion, repetitions had no effect on accuracy. The accuracy for one explosive cycle is lower than for 5 or 10 cycles. However, there was no significant improvement between 5 and 10 cycles.

## 4. Discussion

This study highlights the effect of different movement characteristics on the estimation of HJC location, using a functional approach. The results were obtained using simulated movements in conjunction with a model accounting for noise. Certain limitations are associated with the method. The hip was represented as a ball-and-socket joint. However, there are no mechanically perfect ball-and-socket joints in the human body. The real instantaneous HJC may vary according to the thigh position. The model used to account for skin movement was based on non-invasive measurements and its amplitude was determined from athletes' clusters deformation. The skin movements were qualitatively comparable with results reported in the literature using a different experimental approach [4]. Although the markers were placed far from the joints in order to minimise the effect of skin movement, this was still probably underestimated. It is also possible for a cluster to move with respect to the bone without deformation.

The errors in HJC location were based on a kinematics model and on a single sphere fitting algorithm. The mean error (4.0–7.9 mm) was consistent with the values reported by [14] using a mechanical linkage (between 4.3 ± 0.2 and 9.1 ± 1.5); whereas a higher error value (11.8 ± 4.1 mm) was observed with living subjects [8]. However, the range of motion was greater than in the latter study (Table 1), because sportsmen in general and gymnasts in particular are more supple. For this reason the relationship between the tests was considered to be more important than the individual accuracy measurement.

The present paper corroborates the conclusions of [14]. The implementation of the test caused only minimal variations in HJC accuracy; the retained algorithm [9,10] was robust. However, the effects of the nature, type and number of cycles were statistically significant.

### 4.1. Nature of movement

In the noise model used in this study the effect of skin movement depended mainly on the nature of movement. Thus, the nature of the movements offers a compromise between a variety of postures and the effect of skin movement. Without taking into account the type of movement and the number of cycles, limited movements were more adapted for an accurate estimation of HJC. However, these include both the best and the lowest results. The greatest accuracy was obtained with 10 cycles composed of limited FE/AbAd/Cir movements. Conversely, a single limited FE/AbAd movement yielded the less accurate results. The full movement permitted the execution of more postures than the limited movement, even though the cluster deformation was higher. For the explosive movements, velocity increased the cluster deformation and the trials present fewer samples per cycle. On the whole, the postures achieved during full and explosive movements yielded data with noise levels that were too high. The increase in range and velocity of a motion is detrimental to accuracy, as the additional postures did not compensate for cluster deformation. These results should be moderated by the interactions involving the type of movement and number of cycles.

### 4.2. Interaction between nature, type and number of cycles

Many interactions were evidenced between the nature and the type of movement. It was difficult to choose between Cir and FE/AbAd. Indeed, accuracy differed according to the nature of movements. However, the combination FE/AbAd and Cir improved accuracy in all cases. The FE/AbAd/Cir type was robust, as it was only minimally influenced by the nature of the movements. Thus, the variety of postures obtained using different types of movement is always positive in terms of accuracy. This result partly accounts for the less accurate estimations reported by Bell et al. [7] than those reported by Leardini et al. [8], where Cir was added to FE/AbAd.

The number of cycles is not systematically a factor of accuracy. The adequate number of cycles mainly depends on the nature of the movement. For example, full FE/AbAd/Cir appeared more adapted than limited movements for a short test (one cycle). Limited movements require many cycles in order to increase accuracy. The repetitions result in new postures due to the motion variability. The quantity of samples is a positive factor provided that the noise levels remain not too high. With larger movements, one cycle (full) or five cycles (explosive) is sufficient. Introducing additional cycles do not decrease the error of HJC estimation, as the clusters are affected by a high level of noise. The variability and the range of the motion were not complementary each other.

### 4.3. Perspectives

Using the simulated noise model and the reference kinematics, many other functional approaches could be tested. The effect of the algorithm or of the post-processing can thus be evaluated. For example, the solidification procedure used in this study allowed removing the clusters that were most distorted due to random and continuous noise. This procedure could interact with the nature of the movements in order to improve accuracy. The noise model could also be improved on, or adapted to other research topics. Finally, invasive methods or imaging methods could be used to further validate both the noise model employed and the results obtained using the simulation.

## 5. Conclusion

This study showed that the nature of movement, the type and the number of cycles have a significant effect on the HJC estimation, and that these characteristics of the movement interact. The choice is important to ensure an accurate estimation. Trials with 10 limited cycles of flexion-extension, abduction–adduction and circumduction movements proved the most accurate for estimating the hip joint centre. Accuracy was mainly improved by associating different types of movement. A limited type of movement proved better than large motion amplitude, as the additional postures were affected by high levels of noise. However, 10 cycles were required. For trials involving a single cycle, large movements were the most adapted.

## Acknowledgments

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## Appendix A

### A.1. Details of the solidification procedure

The iterative search and elimination procedure is based on the relative values of the angles (rad) and lengths (m) ($\theta_j^t, L_j^t$, for $j = 1, 2, 3$ or 4, 5, 6), expressed with respect to the mean values ($\overline{\theta}_j, \overline{L}_j$). Cluster *t* which yielded the highest value for Eq. (A.1) is eliminated.

$$\sum_{j=1}^{3}\left(\frac{\theta_j^t-\overline{\theta}_j}{\overline{\theta}_j}\right)^2+\left(\frac{L_j^t-\overline{L}_j}{\overline{L}_j}\right)^2 \tag{A.1}$$

The process was repeated on the pelvis in order to eliminate 10% of the experimental frames, then on the thigh so that only 80% of the frames remained. An optimal cluster was calculated as the mean of the remaining clusters. Then, the three measured markers positions were replaced according to this optimal cluster.

### *A.2. Perfect movement*

The coordinates were collected using markers placed on the pelvis ($R1$) and thigh ($R2$) of one subject. HJC location was estimated in $R1$ (${}^1H$) and in $R2$ (${}^2H$) using a functional approach. The Cardan angles ($\alpha, \beta, \gamma$) were derived from the orientation matrices of the thigh with respect to the pelvis (${}^1_2R$). The Cardan angles of the eliminated frames were interpolated using a spline cubic method. Based on these coordinates $[\alpha, \beta, \gamma, {}^1H, {}^2H]$, the $j$th thigh marker position with respect to $R1$ at time $t$ was calculated as follows:

$$ {}^1P_j^t = {}^1_2R \times {}^2P_j + {}^1H - {}^1_2R \times {}^2H \qquad \text{(A.2)} $$

where ${}^2P_j$ corresponds to the $j$th thigh marker position with respect to $R2$.

### *A.3. Details of the noise model*

The variation in length was expressed with respect to the reference lengths ($L_j^{\text{Ref}}$) as measured during the static posture. For each cycle, the range of the deviation was obtained by eliminating 5% of the extreme values. An average deviation ($\bar{D}_{j,k}$) was then calculated for all trials (see Table A.1):

$$ \bar{D}_{j,k} = \frac{1}{10}\sum_{\text{cy}=1}^{10}\frac{1}{T}\sum_{t=1}^{T}\frac{L_{j,k}^{\text{cy},t} - L_j^{\text{Ref}}}{L_j^{\text{Ref}}}, \quad \text{for } j = 1, \ldots, 6 \qquad \text{(A.3)} $$

Generally, the curves present a similar shape. The amplitude of the explosive motion is greater than for the full movement which, in turn, is greater than for the limited movement. A Gaussian function was preferred to the sine functions used in previous studies [12,15,16] for modelling continuous noise. This aspect was specific to the nature of movement ($k$), marker ($j$) and coordinate ($i$) and was repeated for all cycles. At the instant $t$, the artificial noise was expressed as follows:

$$ N_{i,j,k}^t = (a1 \times a2_{j,k} \times a3)\exp^{\frac{-(t-b)^2}{2c^2}} + d \qquad \text{(A.4)} $$

where $a_{j,k}$ depended on marker ($j$), nature of movement ($k$) and a two random coefficients: $a_{j,k} = a1 \times a2_{j,k} \times a3$, with $a1 \in \{-1; 1\}$ and $a3 \in [0.9; 1]$. The amplitude depended mainly on the markers and the nature of movement, $a2_{j,k}$ depicting the maximal systematic error on coordinates. The coefficients $a2_{j,k}$, summarised in Table A.2, were adjusted in order to obtain an average deformation similar ($\pm 0.1\%$) to the experimental deformation.

$b$ and $c$ were random values ranging between 35–65% and 5–15% of the cycle duration, whereas $d$ designated the measurement error of the stereophotogrammetric system. According to [15] study, this error was considered as random noise with a normal distribution (mean = 0 mm, standard deviation = 0.615 mm).

Table A.1
Range of deformation (% of the reference lengths) of the clusters

| | Limited | Full | Explosive |
|---|---|---|---|
| $L_1$ | 3.4 | 4.8 | 6.9 |
| $L_2$ | 2.5 | 3.7 | 4.2 |
| $L_3$ | 3.0 | 4.9 | 6.1 |
| $L_4$ | 4.9 | 6.6 | 6.8 |
| $L_5$ | 5.0 | 7.6 | 8.2 |
| $L_6$ | 3.1 | 4.8 | 5.0 |

The mean value was calculated for each nature of movement and for each length.

Table A.2
Coefficients of deformation (mm) $a2_{j,k}$ according to markers ($M_j$, $j = 1, \ldots, 6$) and nature of movement ($k$)

| Natures ($k$) | $M_1$ | $M_2$ | $M_3$ | $M_4$ | $M_5$ | $M_6$ |
|---|---|---|---|---|---|---|
| Limited | 2.84 | 2.35 | 1.52 | 4.55 | 4.13 | 2.25 |
| Full | 4.45 | 2.92 | 3.38 | 6.14 | 5.51 | 4.78 |
| Explosive | 6.55 | 4.22 | 2.85 | 6.34 | 5.60 | 5.37 |

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