ACOUSTICS 2012

Experimental study of the musician / instrument interaction in the case of the concert harp

D. Chadefaux[a], M. Wanderley[b], J.-L. Le Carrou[a], B. Fabre[a] and L. Daudet[c]

[a]Equipe LAM - d'Alembert, 11, rue de Lourmel, 75015 Paris, France
[b]IDMIL / CIRMMT McGill University, 555, Sherbrooke Street West, Montreal, Canada H3A 1E3
[c]Institut Langevin " Ondes et Images ", 10 rue Vauquelin, 75005 Paris, France
chadefaux@lam.jussieu.fr

Over the years, a trained musician develops the ability to produce a sound as desired: the player's gestures are precisely executed in order to control each note. In the case of the concert harp, a previous study had underlined the characteristics of string plucking, both highly reproducible and player-specific. However, the whole harpist's body is obviously also involved in a musical performance. Therefore, the present paper investigates the player / harp interaction, by characterizing the musical gestures in relation to the musical interpretation. We have captured the motion of three skilled harpists playing an excerpt of Debussy's Danse Profane, using a motion tracking system based on infrared cameras with acoustical measured synchronously. A set of kinematic and dynamic descriptors has been extracted from the collected data. They provide features of instrumental gestures (directly related to the sound production) and ancillary gestures (not directly involved in the sound production). Results indicate that the posture strategy is of great importance for harpists, and a correlation is made between the harpist gestural behavior and harp teachers recommendations. It is also shown that harpists perform remarkably reproducible gestures related to her/his musical strategy.

1 Introduction

While performing a piece, a musician has to deal with a trade off among simultaneous movements objectives. First, the musician has to put the instrument into vibration. Then, she/he has to spare energy and prevent articular and muscle pain to be able to perform the entire piece. Finally, she/he has to eventually interact with other musicians (communicative intention) and audiences (emotional / musical intention). These objectives have already been investigated in the case of drumming [1, 2], piano [3, 4], and violin [5], among others instruments [6]. Few studies focus on plucked strings instruments and especially on the concert harp. However, skilled harpists claim that the concert harp is a physically demanding musical instrument. Indeed, it is about 1.8 m tall, weights about 35 kg and is played tilted on the right shoulder and the knees. For information purpose, the *tessitura* of a concert harp is from about 31 (Cb0) to 2960 Hz (Gb6), with string tension from 200 to 500 N. The latter value is a boundary beyond which string instruments are not played directly with the finger but more likely with a plectrum or a hammer. Considering isolated notes in the middle of the harp *tessitura*, the plucking force has been evaluated up to 15 N for a string tension of 260 N [7]. Therefore, the postural and gestural strategies seem to be of great importance to play the harp.

The present paper describes results from an ongoing exploratory study of the musical performance objectives in the case of the concert harp. We investigate postural and gestural characteristics, within the harpist and harp motions during playing. For this purpose, we first describe the experiment carried out in order to measure audio signals and motion performances of harpists. Then, a set of kinematic parameters that describe the harpist's performance is provided. Finally, these descriptors are analyzed and confronted to harp teachers recommendations and musical context.

2 Experimental procedure

2.1 Experimental setup

To study the musician / instrument interaction, a specific experimental setup was designed. It is mostly based on capturing the motion of reflective markers fixed on harpists by using a tracking system based on six infrared cameras (Vicon system 460). Acoustical signals have been measured synchronously thanks to simultaneous recordings of performances with standard DV camera. Reflective markers have been disposed on musician according to the Plug-in-Gait model (VICON, Oxford Metrics Ltd, Oxford, UK), neglecting the chest, since the harp would have obstructed these markers. The compromise between motion capture sampling rate and spatial range led us to set the cameras at 250 frames per second, allowing the capture of the whole set of markers except those head. Figure 1-a shows a picture of a harpist during measurements. Thanks to the reflective markers positions, simplified link-segments models of the body (where each segment corresponds to a limb) and the harp were constructed (Figure 1-b). Note that the black circles and sticks represent the harpist whereas the grayed ones represent the harp.

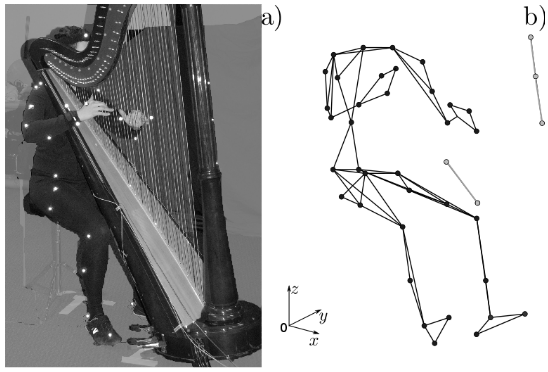

Figure 1: Picture of a harpist during the measurement session (a) and extracted position of body segments (b).

2.2 Measurement protocol

Harp players were asked to play the full Debussy's *Danse Profane* on a concert harp (Aoyama Orpheus 46 strings). In order to highlight players' gestures characteristics, three harpists were asked to participate, and all performances were repeated three times. Among the harpists, two of them are professional orchestra musicians, noted H_1 and H_3 in the present paper, while the third is a non-professional musician, who regularly practices the concert harp, noted H_2. Harpists were given time (as long as necessary) as an adaptation period to get used to the harp and the general measurement context.

2.3 Data segmentation

The beginning of the piece contains a repetition of three different octave intervals, referred as *note* and denoted D, A and B in the following. Only the left hand is involved and no change in the harp pedals configuration is needed to perform

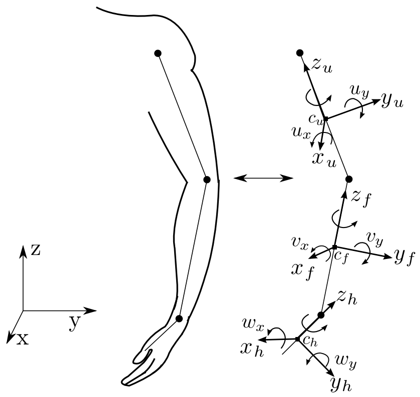

Figure 2: Anatomical arm segments showing the global and anatomical reference systems.

this excerpt. Hence, we restrict the present analysis to this part. The score of this excerpt is shown in Figure 4.

To characterize the strategy used to perform a note, gesture and sound associated to this note have to be isolated. Following [8], the sound-producing gesture related to a note is here defined as the plucking action itself combined with the previous hand trajectory focusing the strings and the following hand trajectory leaving the strings. Practically, the gesture onset is estimated at the last zero value of the hand velocity before the acoustical onset, i.e. approximately at the instant the harpist gets in contact with the strings. To this end, each acoustical onset, i.e. the instants strings are released by the harpist have to be highlighted. Classical onset detection methods [9, 10] are applied to the acoustical signals.

3 Kinematic analysis

3.1 Global and anatomical reference systems

The raw motion capture data collected consist in markers coordinates over time in the global system of reference (X,Y,Z) defined in Figure 2. This frame of reference is fixed in the laboratory and its origin is under the harpist seat. X is the forward / backward direction, Y is the medial / lateral direction and Z is the gravitational axis. Most analyses were done in the global system of reference, however, to perform joints kinematic analyses, anatomical systems of reference fixed to each arm limb segment are needed. They are denoted (x_u, y_u, z_u), (x_f, y_f, z_f), and (x_h, y_h, z_h) in Figure 2 for upperarm, forearm and hand segments, respectively. Within each arm-segment, the anatomical axis system is set with its origin at the center of mass of the segment with z-axis along the limb-segment axis. The center of mass of each segment is known based on the harpist's mass combined with anthropometric data of the relative limb's mass [11].

3.2 Harp performance descriptors

3.2.1 Harpist / harp posture

To describe the harpist posture, a set of descriptors was defined based on kinematic data of the whole harpist body and the harp motion. Specific markers, which are placed on the acromioclavicular joints, the anterior and superior iliac spines, and the lateral epicondyle of the knees, are used to compute the following descriptors during performances:

- harp tilt,
- back bending relative to the ground,
- hips opening,
- shoulders rotation related to hips,
- and hips rotation related to harp.

3.2.2 Arm posture

To investigate arm posture strategy during playing, arm joints rotations are evaluated. A kinematic model of the arm is used to transform Cartesian coordinates of joint positions in the global reference system into body-related angles. Shoulder is modeled as ball-and-socket joints with three rotary degrees of freedom while elbow and arm are modeled as ball-and-socket joints, with two rotary degrees of freedom [12, 13]. Using anatomical axes defined in Figure 2, their relationships to body description are:

- Shoulder: abduction / adduction (rotation u_x), anteversion / retroversion (rotation u_y) and rotation (rotation u_z) of the upperarm,
- Elbow: flexion / extension (rotation v_y) and pronation / supination (rotation v_z) of the forearm,
- Wrist: radial / ulnar deviation (rotation w_x), and palmar flexion / dorsal extension (rotation w_y) of the hand.

Note that the reference left arm position is taken right along the body, with palm toward the body.

3.2.3 Arm and hand motions

In order to describe harpist's arm kinematics, a total description in the three dimensions (position, velocity and acceleration) is provided by a stick diagram in Figure 5. Each body segments, e.g. hand, lower-arm and upper-arm, is represented by a straight line at each instant of a note production. For a better readability of the figure, note that the data is five times undersampled. Furthermore to investigate the repeatability and characteristics of sound producing and ancillary (not directly involved in the sound production [14]) gestures relative to the played score, we focus on the hand movement in the (x0y) plane.

3.3 Dynamical analysis

Previous section dealt exclusively with harpist movement and posture analysis, without regard to forces. However, to pinpoint causes and strategies, which are behind the harpist gesture, their patterns have to be known. Using inverse dynamics [15], reaction and moments at each arm joint can be computed. From these physical parameters, power and therefore work can be reached. The entire work generated by harpist's arm muscles is then computed. Combining this method with an assumption of the energy transferred by the harpist's fingers to the strings based on classical string modeling [16] and the known orders of magnitudes of involved parameters [7], the efficiency of a left arm gesture is evaluated.

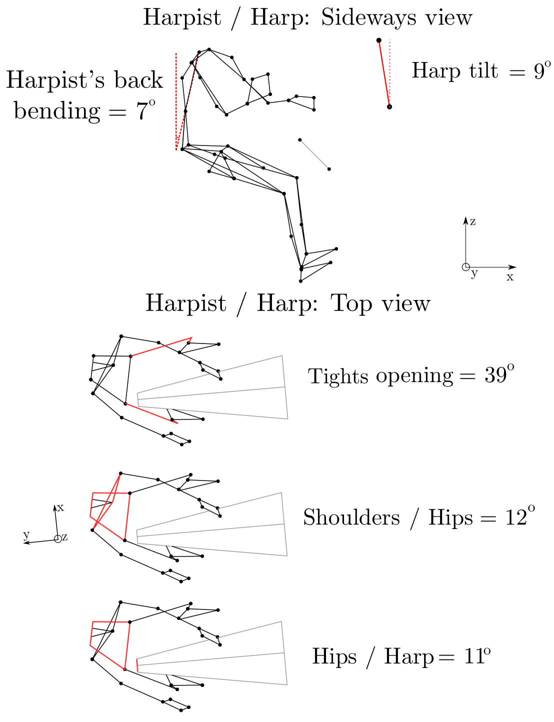

Figure 3: Harpist posture related to the concert harp. The mean position is computed on the three repetitions of the musical excerpt by the harpist H_1.

4 Discussion

In the following, descriptors are computed for one harpist (H_1) playing the musical excerpt shown Figure 4.

4.1 Harpist playing posture

4.1.1 Geometrical harpist / harp relationship

Figure 3 shows measured characteristics of the general harpist's posture related to the concert harp (cf. Section 3.2.1) computed in playing conditions over the three repetitions of the musical excerpt. Each angle is computed between red lines in the associated scheme. First, the small uncertainties (evaluated less than 0.5 % of the mean position) validate our experimental protocol. They tend also to indicate that the harpist and the harp are very stable, whatever the performed note. Secondly, as already mentioned, the harp is played tilted toward the right shoulder. Therefore, the tights have to let the instrument through, with an opening measured to 39°. Then, it appears that harpist stands quasi upright (the back is bent over about 7°), but sideways regarding to the strings' plane. Finally, a non negligible angle exists (about 12°) between the hips and the shoulders with the left shoulder ahead.

These experimental results correspond to harp teachers advices about the posture to adopt. Indeed, according to teachers, the harp tilt is the most important parameter to find the right posture. For purposes of convenience, the harp has to be tilted in order to be in balance and thus minimize the weight shared between the right shoulder and the knees. Furthermore, harpist's spinal column has to be straight combined with slight torsion toward the left side in order to reach the more distant strings and avoid back injuries. Moreover, the harp is placed crosswise to the performer in order to keep the back straight.

Table 1: Left arm joints rotation (deg) computed during harp performance according to systems of reference defined in Figure 2. The mean is computed on each note separately over the three repetitions of the musical excerpt. The reported uncertainty represents a 95% confidence interval.

Octave type	D	A	B
Shoulder abduction (u_x)	23.7°	21.8°	23.6°
±	(0.1°)	(0.2°)	(0.1°)
Shoulder anteversion (u_y)	47.5°	49.6°	47.7°
±	(0.1°)	(0.2°)	(0.2°)
Shoulder rotation (u_z)	22.2°	19.3°	20.0°
±	(0.1°)	(0.2°)	(0.2°)
Elbow flexion (v_y)	122.6°	119.6°	122.6°
±	(0.1°)	(0.3°)	(0.2°)
Elbow supination ($-v_z$)	17.3°	18.1°	17.4°
±	(0.1°)	(0.2°)	(0.3°)
Ulnar deviation ($-w_x$)	45.0°	39.8°	44.9°
±	(0.2°)	(0.4°)	(0.3°)
Hand dorsal extension ($-w_y$)	25.8°	27.5°	26.0°
±	(0.1°)	(0.2°)	(0.3°)

4.1.2 Left arm joints posture

Table 1 presents arm joints rotations in the associated anatomical reference systems defined in Figure 2. No fundamental difference appears between the three produced notes D, A and B. As previously shown, uncertainties are low (smaller than 1°), showing the high repeatability of the harpist posture over the three excerpt's executions. As arm joint rotations are highly dependent on the harpist morphology and the distance of the plucked strings, the low uncertainties are due to the small *tessitura* range involved in the present musical excerpt. Regarding the arm posture, harp teachers explain that the elbow has to be raised at about 45°ahead relative to the gravitational axis. The shoulder anteversion we measured, which leads to the raise of the elbow, is about 48°. Again, this order of magnitude matches harp teacher recommendation. The hand dorsal extension, i.e. the angle between forearm and hand, is evaluated to 27°. Harpists recommend to keep a slight angle between hand and forearm in order to facilitate the projection of fingers into the palm of the hand after plucking. In this situation, only the flexor digitorum profundus (muscle in the forearm that flexes the fingers) is involved, making easier the reopening of the fist and hence fingers relaxing.

4.2 Upperlimb motion in playing context

After investigating the global posture adopted by harpists, let us analyze the kinematic of the arm in playing. Figure 5 presents a stick diagram of the harpist left arm between two notes. The latter has been choosen because of its relevance relative to the entire recorded note panel. It conveys how the global arm movement is shared between arm joints. The shoulder appears to be quite still whereas elbow wrist and hand move with an increasing magnitude. As expected because of their relative mass, the shoulder appears to be the stablest joint, controlling the arm movement.

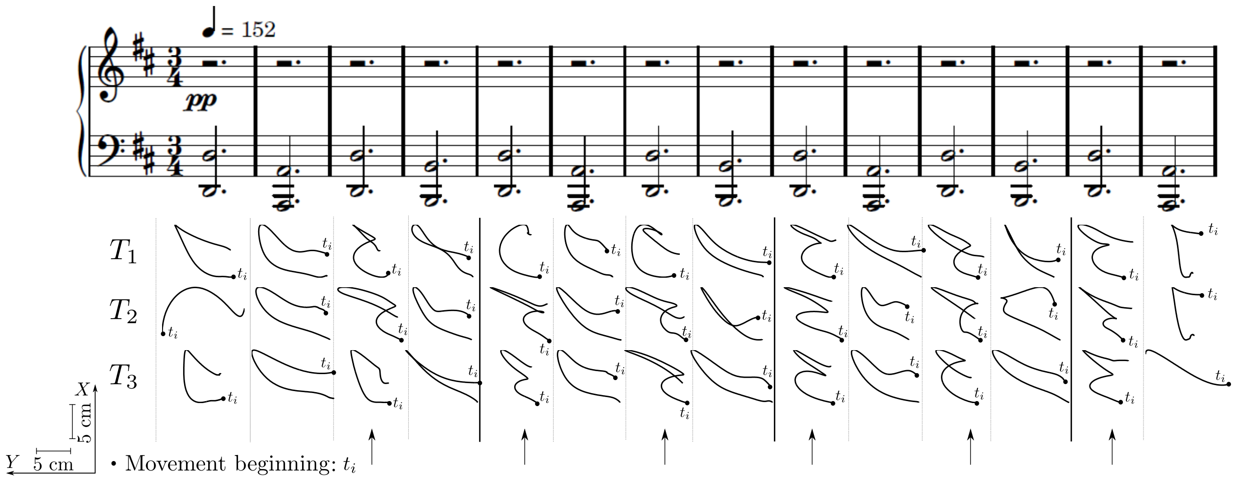

Figure 4: Repeatability and characteristics of left hand movement for a harpist performing the Debussy's *Danse Profane* excerpt. t_i correspond to the beginning of the movement.

As the hand is the limb with the more emphasis on movement relative to other arm-segments, we analyze its movements in order to investigate sound producing and ancillary gestures, i.e. hand movements during the plucking action and after it. Figure 4 presents the left hand movement in the (x0y) plane for all the notes performed throughout the three executions denoted $T_{1..3}$ in Figure 4. The analysis of these movements show repeatable patterns for a given bar during the three executions of the musical excerpt. After performing *A* and *B* notes, the hand moving back to the *D* strings has a smooth bell-shaped trajectory. On the contrary, once the *D* interval is played, the hand moves forward to *A* or *B* strings with more complex and specific movements. As playing the A or B strings diers little in the technique and the posture from playing the D ones, the two dierent patterns observed can be explained by the harpist strategy relative to the musical phrase, as can be heard on the recordings. Indeed, assuming that he/she interprets the excerpt built on the three repetitions of the four octaves D-A-D-B, it would explain that the first and third bars (D) have different emphasize than the second (A) and fourth (B) bars in each sequence, and therefore their more complex movements. These notes are highlighted by arrows in Figure 4. Note that the first bar is not considered because of its ambiguous interpretation.

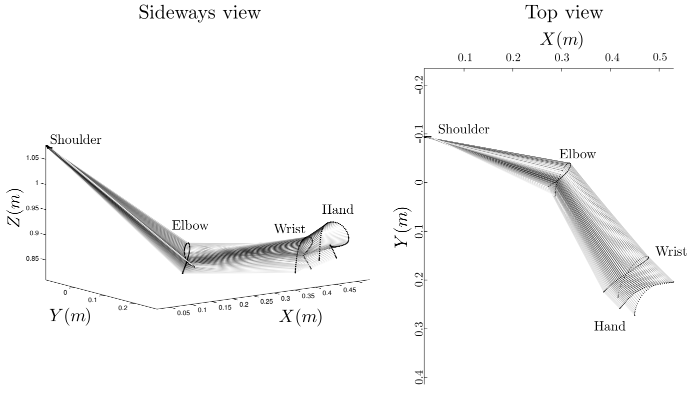

Figure 5: Example of a left arm gesture corresponding to the performance of one octave interval.

Table 2: Left hand gesture efficiency computed during harp performance. The mean is computed on each note separately over the three repetition of the musical excerpt. The reported uncertainty represents a 95% confidence interval.

Octave type	D	A	B
Gesture Efficiency ±	0.092 % (0.005 %)	0.021 % (0.003 %)	0.028 % (0.002 %)

4.3 Arm gesture efficiency

The amount of energy generated by the harpist's left arm relative to the one transferred to the strings is now computed as explained Section 3.3. Results, shown in Table 2, indicate that the arm gesture efficiency is really small (less than 0.01%). Hence, the complex gestures we describe in the last paragraphs are very energy expensive relative to the plucking action. Therefore, this result underlies the importance of ancillary gestures in the harpist strategy. Furthermore, the efficiency estimated for the D note is about 4.5 times higher than the one computed for A and B notes, which are approximately equal. This observation can again be related to the harpist interpretation of the musical phrase.

5 Conclusion

In this paper we presented a preliminary study of the musician / instrument interaction in the case of the concert harp. We investigated the general harpist posture in relation to the instrument and the arm behavior while plucking strings. For this purpose, kinematic and dynamic analyses of harp playing have been investigated.

Measurements showed that the global posture of harpists is very stable during playing. It is shown that harp teachers recommendations about the posture to adopt correlate well with our measurements. Although the arm is directly involved in the sound production, the relation between each arm-limb stays constant during the selected excerpt performance. The shoulder can be seen as a fixed point where the producing gesture control is done. Besides, the hand appears to perform the more accentuated movements. These measurements have been confirmed by harp teachers recommendations about the posture to adopt to play concert harp. Considering one harpist, repeatable patterns of the gestures' shapes have been evaluated on three executions. Finally, regarding a given note at a particular place in the musical phrase, repeatable pattern of the hand gestures (sound producing as well as ancillary) and arm efficiency have been evaluated for a particular musician. This fact suggest that the harpist musical interpretation is conveyed in hand movements.

Further work will be carried out to investigate different gestural behavior depending on the musical skills of the harpists. For instance, a classical video and audio analysis will be helpful to pinpoint the relation between harpist gestures and his/her musical intention. Finally to investigate the trade off among the different musical movements objectives (to play the piece / to prevent muscles and joints injury / to communicate with audience and musicians), a more detailed dynamic study of musical gestures will be necessary to characterize the harpist control strategy.

Acknowledgments

The authors would like to thank Carolina Brum Medeiros and Mahtab Ghamsari-Esfahani for their help during measurements, Jennifer Swartz for her interest in this study, and the harpits who participated in this study: Marie Denizot, Eveline Grégoire-Rousseau, Caroline Lieby-Muller, Antoine Malette-Chénier, Magali Monod-Cotte and Mary Elizabeth Sutherland.

References

[1] S. Dahl and A. Friberg. Expressiveness of musician's body movements in performances on marimba. In *Gesture Workshop'03*, pages 479–486, 2003.

[2] S. Dahl. Playing the accent - comparing striking velocity and timing in an ostinato rhythm performed by four drummers. *Acustica United with Acta Acustica*, 90(4):762–776, 2004.

[3] D.A. Winter. *Biomechanics and Motor Control of Human Movement, Fourth Edition*. John Wiley & Sons, Inc. Hoboken, New Jersey, 2009.

[4] I. Poggi. Body and mind in the pianist's performance. In *Proceedings of the 9th International Conference on Music Perception and Cognition (ICMPC9)*, pages 10044–1051, Bologna, Italy, 2006.

[5] N.H. Rasamimanana, E. Fléety, and F. Bevilacqua. Gesture analysis of violin bow strokes. In *Lecture Notes in Computer Science*, volume 3881, pages 145–155. Springer Verlag, 2006.

[6] F.J. Bejjani and N. Halpern. Postural kinematics of trumpet playing. *Journal of Biomechanics*, 22(5):439–446, 1989.

[7] D. Chadefaux, J.L. Le Carrou, B. Fabre, and L. Daudet. Experimentally based description of harp plucking. *J. Acoust. Soc. Am.*, 131(1):844–855, 2012.

[8] A.R. Jensenius, M.M. Wanderley, R.I. Godøy, and M. Leman. *Musical Gestures: Sound, Movement, and Meaning*, chapter Musical Gestures: concepts and methods in research,, pages 12–35. Routledge, New York, 2009.

[9] J.P. Bello, L. Daudet, S. Abdallah, C. Duxbury, M. Davies, and M. Sandler. A tutorial on onset detection in music signals. *IEEE Transactions on Speech and Audio Processing*, 13:1035–1047, 2005.

[10] C. Duxbury, J.P. Bello, M. Davies, and M. Sandler. Complex domain onset detection for musical signals. *6th International Conference on Digital Audio Effects (DAFx)*, 1:90–94, 2003.

[11] O. Ortmann. *The Physiological Mechanics of Piano Technique*. E.P. Dutton, New-York, 1929, reprinted 1962.

[12] R. Raikova. A general approach for modelling and mathematical investigation of the human upper limb. *Journal of Biomechanics*, 25(8):857–867, 1992.

[13] R. Riener and A. Straube. Inverse dynamics as a tool for motion analysis: arm tracking movements in cerebellar patients. *Journal of Neuroscience Methods*, 72(1):87–96, March 1997.

[14] M.M. Wanderley, B. Vines, Middleton N., C. McKay, and W. Hatch. The musical significance of clarinetists' ancillary gestures: An exploration of the field. *Journal of New Music Research*, 34(1):97–113, 2005.

[15] B. Bresler and J. Frankel. Forces and moments in the leg during level walking. *Trans. ASME*, 72:27–36, 1950.

[16] A. Chaigne and J. Kergomard. *Acoustique des instruments de musique*. BELIN, 2008. ISBN 978-2-7011-3970-8.