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Harp plucking robotic finger

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Abstract— **This paper describes results about the development of a repeatable and configurable robotic finger designed to pluck harp strings. Eventually, this device will be a tool to study string instruments in playing conditions. We use a classical robot with two degrees of freedom enhanced with silicone fingertips. The validation method requires a comparison with real harpist performance. A specific experimental setup using a high-speed camera combined with an accelerometer was carried out. It provides finger and string trajectories during the whole plucking action and the soundboard vibrations during the string oscillations. A set of vibrational features are then extracted from these signals to compare robotic finger to harpist plucking actions. These descriptors have been analyzed on six fingertips of various shapes and hardnesses. Results allow to select the optimal shape and hardness among the silicone fingertips according to vibrational features.**

I. INTRODUCTION

First straightforward mechanical automatons, musician robots are now able to produce realistic sounds and can even be compared to real musicians. A detailed history and evolution of musician robots is given in [1], [2], [3], [4]. Two particularly striking examples are the Waseda Flutist Robot (WF-4RII) [5] and a violin playing robot [6]. Both are studied in comparison to real musician's performance. Dealing with acoustical signals, features extracted from time-frequency analyses indicate that produced sounds seem to be realistic. Musician robots can be valuable to study musical instruments. Indeed, their investigation in playing conditions requires a highly controllable and repeatable excitatory mechanism. Several apparatus were already designed to study wind instruments, as blowing machines. Their development began in 1941 [7] and is still in progress to study reed instruments [8], air-jet instruments [9] and brass instruments [10]. Regarding string instruments, the first artificial bow was designed in 1957 [11] to investigate violin family instruments. Mechanical systems have been developed for plucked string instruments. These devices are based on a wire placed around a string and pulled until it breaks. Note that the wire can be automatically [12] or manually pulled [13]. However, these systems are far from reproducing real plucking, especially for the harp. Considering the classical playing technique, the fingertip slips on the string and imposes initial conditions which are a complex mix of displacement, velocity and rotation [14]. Unlike a wire, a robotic finger could provide these particular initial conditions. The present paper describes results from the development of a robotic finger designed to pluck the harp strings. As this robot is designed to reproduce the harpist plucking, an evaluation by comparison with harpist's performances is required.

Our paper is organized as follows. First, we describe the harp plucking and the artificial finger we designed. Then, an experiment is set up to measure the artificial finger displacement during the plucking and the soundboard vibrations. Hence, a comparison between the artificial finger and harpist plucking action is obtained. Finally, we evaluate the reliability of the designed system for reproducing harpists' plucking gestures.

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II. PLUCKING DESCRIPTION

In a previous study [14], a well-controlled experimental setup had been designed to study the harp plucking action. Measurements were performed with ten harpists in several musical contexts. About 150 plucking actions of the 30th string (D♭2 at a fondamental frenquency of 138.6Hz) have been analyzed. They were extracted from chord and arpeggio sequences, performed with the annular and the forefinger. The investigation of this database had shown that the motion is performed in the plane perpendicular to the direction of the strings and that it can be decomposed into three sequences [14], [15], [16]. First, the sticking phase (from about 100ms to 400ms), when the finger and the string move parallel to each other at the contact point, $\forall t \in [t_c; t_s[$. Then, the slipping phase (about 3ms), when the string slips on the finger surface with opposite direction $\forall t \in [t_s; t_r]$. Finally, at a time denoted t_r, the string is released and its current characteristics (shape, velocity, ...) turn to be of prime importance on determining the produced sound. It defines, indeed, the initial conditions of the string free oscillations $\forall t > t_r$.

The study of these plucking actions shows different kind of trajectories, depending mostly on the performer and the technique she/he used. The movement of the harpist's finger can indeed be almost straight as well as really sinuous. Furthermore, a striking result is that the whole panel of plucking actions has been performed in a square with sides 20mm long. Regarding the finger behavior, 97% of the evaluated maximum velocities is less than 1.5m/s while 90% of them is less than 1m/s. The force applied by the finger on the 30th string is up to 15 N. Each harpist provides specific but highly reproducible initial conditions to the string vibrations. Its displacement, velocity and angular deviation have been measured at the release instant up to 8mm, 5m/s and 80°, respectively.

III. ROBOTIC FINGER DESCRIPTION

A. Description

As the robotic finger is designed to pluck harp strings, it has to be sturdy and at least as repeatable and accurate than a real harpist. Besides, it has to satisfy the specifications reported in Tab. I. They are based on the plucking properties presented Sec. II.

TABLE I
ROBOTIC FINGER SPECIFICATIONS.

Data	Maximum value
Force	15N
Area of use	$20{\times}20\text{mm}^2$
Velocity of the fingertip	1.5m/s
Trajectories duration	200ms

The designed robotic finger is presented in Fig. 1. Its base was conceived to be attached to the harp's column while preventing the robot to be prone to the harp vibrations. As the plucking action takes place in the plane perpendicular to the direction of the strings, the robot is chosen to be planar with two rotational joints. The conception of the yellow-arm in Fig. 1 works toward the achievement of the given force specification. Also, its geometry allows the length comparison of the last two human forefinger phalanxes, i.e. a length of 45mm.

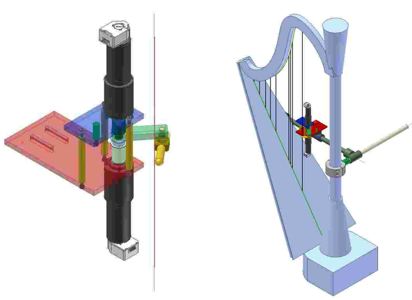

Fig. 1. Artificial finger on its frame (left) and rigidly fixed on the harp's column (right).

As a matter of compactness, both motors are placed at the robot's base. A belt is used to transmit motor's torque to the second joint, as present in Fig. 2. The chosen belt has a length of 177.5mm, and a thread of 2.5mm. Since the diameter of the pulleys mesures 17mm, the spacing is equal to $\frac{L-\pi D}{2}=$ 62.04mm, ceiling to 62.1mm. As the harpist finger movement is enclosed in a square area of about 20mm side. The robotic finger setup allows the end-effector to follow any trajectory in a 400mm^2. In order to perform the specific force and velocity within this area, the actuation system is based on chain compound of Maxon RE35 motors, associated with Maxon GP 42C reducer and Maxon HEDL 5540 encoder.

This robot is position-controlled [17], and the frequency of this control loop is 1kHz. Besides, a graphical user interface allows to define the trajectory the robot has to follow.

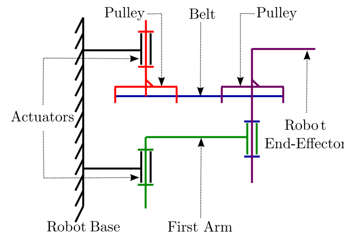

Fig. 2. Robot kinematics

B. Fingertip shape and material

Fingertip shape and material are important aspects of the design. Both define the friction behavior between finger and string. The most suitable material for a robotic finger depends on various properties, such as friction / adhesion, mechanical properties, durability as well as suitability for tactile sensing [18], [19]. In touch experiments using a reference textile (normal loads vary between about 0.2N to 15N), the silicone's and the human skin's friction coefficients are found to be close [20]. Thus, we chose silicone to mold the pulp of the real finger. As shown in Fig. 3, this piece of silicone is surrounding an aluminum bone. The fingertip's size is similar to a human one.

In order to point out the most appropriate parameters for the fingertip, a parametric study, analogous to [21], is carried out. Three shapes and four materials, defined in Tab. II and shown in Fig. 4, were considered. Note that adding filler increases viscosity and hardness, while adding silicone oil dilutes it and decreases those characteristics.

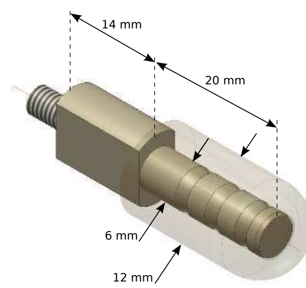

Fig. 3. Description of the Fingertip: bone in aluminum and fingertip in silicone.

IV. EXPERIMENTAL PROCEDURE

A. Experimental setup

In order to evaluate the artificial finger performances in comparison with harpist, a measurement protocol is carried

(a) Top view. (b) Side view.

Fig. 4. Silicone fingertips of three different shapes: B-C-A

TABLE II

SILICONE FINGERTIPS CHARACTERISTICS.

Notation	Shape	Material
A5	A: Cylindrical; round-extremity	Silicone + 5% of filler
A15	A: Cylindrical; round-extremity	Silicone + 15% of filler
A15O	A: Cylindrical; round-extremity	Silicone + 15% of silicone oil
A5L	A: Cylindrical; round-extremity	Silicone + 5% of filler + latex skin layer
B5	B: Cylindrical; float-extremity	Silicone + 5% of filler
C5	C: Plane-parallel	Silicone + 5% of filler

out (Fig. 5-a)). It is based on filming simultaneously the finger's distal phalanx and the string interaction with a high-speed camera while measuring the soundboard vibrations with an accelerometer glued to the bottom of the studied string. The estimation of the finger and the string trajectories is done in the plane perpendicular to the strings' direction by tracking markers positioned at strategic places in the direct view and in a mirror view, as presented in Fig. 5-b). Concerning harpist's finger, the marker is positioned close to the nail, which is assumed to be rigid and have the same movement as the distal phalanx. The robotic finger's marker is placed at the silicone fingertip's extremity since it is assumed to have the same behavior as the robot end-effector. Regarding the string, marker is glued as close as possible to the plucking position. Markers positions presented in Fig. 5-b) were detected automatically through image processing. For each marker, the area of interest containing its image through the high-speed camera is selected by the user, creating the initialization template. Its contour is detected through active-contour modeling [22], allowing the estimation of its center's position. A new template, corresponding to the initial one is then searched in the next image through a block-matching algorithm model [23]. This process is recursively done within the entire set of images for all markers. We note $\tilde{x}$ and $\tilde{z}$ the horizontal marker displacements (in pixel) in the direct and mirror view, respectively. Their real displacements (in meter) are

$$x(t) = \tilde{x}(t)\ K_x^{px2m}\ \cos\theta_1, \quad (1)$$

$$z(t) = \frac{\tilde{z}(t)\ K_z^{px2m} + \tilde{x}(t)\cos\theta_1 K_x^{px2m}\cos 2\theta_2}{\sin 2\theta_2}, \quad (2)$$

with K_x^{px2m} and K_z^{px2m} the pixel to meter ratio, θ_1 the deviation between the image plane of the camera and the string's plane, and θ_2 the angle between the mirror and the string's plane.

B. Measurement protocol

For robotic finger evaluation purpose, a harpist has been asked to pluck eight times the 30th string (D♭2 at 138.6Hz) with the right forefinger. Note that all strings but the plucked one were damped. Fig. 6 presents the performed finger movements over these plucking actions. The averaged finger's velocity at the release instant is estimated at 0.98±0.08m/s.

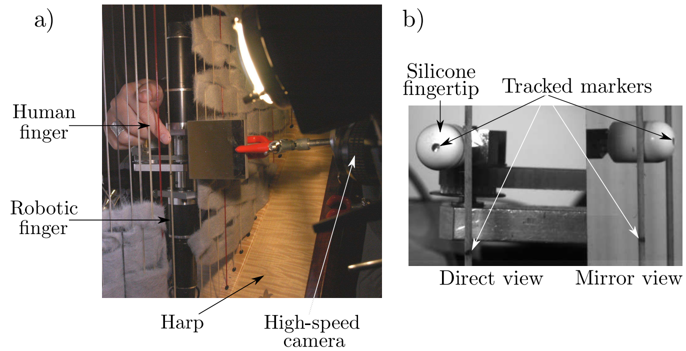

Fig. 5. a) Picture of the experimental setup with a human finger and the artificial one. b) Images obtained through the high-speed camera for a robotic plucking action in both the direct and the mirror views.

This result conveys that these eight plucking actions are relevant relatively to the typical velocity measured on harpists in musical context. Hence, one over these movements has been selected (the grayed one in Fig. 6, for which we estimate a velocity of 0.99m/s) to be injected as reference to the robotic finger. It reproduces the movement with six different silicone fingertips, characteristics of which are presented in Tab. II.

Fig. 6. Harpist forefinger movement during plucking actions. The grayed movement is used as reference for the robot.

V. RESULTS

In the following, the robotic finger is evaluated at different steps of the plucking action. First, the repeatability of the robot end-effector is analyzed. Then, the finger's distal phalanx trajectories are compared with the expected ones. Finally, the resulting soundboard vibrations are investigated.

A. Robotic finger repeatability

Although it is obvious that a servocontrolled DC-motor driven robot is more repeatable than human finger in no-load conditions, the dynamic time warping algorithm [24] confirms the robotic finger is about 82 times more repeatable than the harpist. Thus, the repeatability condition is clearly fulfilled.

B. Plucking action reliability

In order to evaluate the relevance of each silicone fingertip, the measured phalanx trajectories are compared to the robot end-effector and to the reference ones in Fig. 7. The reference trajectory is well-reproduced by the robotic finger. However, a slight deviation appears at the end of the sticking phase and reaches its maximum value at the beginning of the slipping phase t_s. According to [14], it indicates that the higher the finger / string force applied, the more the deviation from the reference because of the local deformation of silicone (Fig. 7). For instance, the fingertip A15O which has the lowest hardness shows the most important difference with harpist finger trajectory at the end of the sticking phase.

Regarding the reference, the sticking and the slipping phases defined Sec. II last 326.6ms and 2.8ms, respectively. Tab. III-a) reports those durations for each silicone fingertip, denoting $\Delta\Phi_c$ and $\Delta\Phi_s$ the sticking and the slipping phases duration, respectively. Sticking phase lasts about 25% longer than expected without outstanding differences between fingertips. On the other hand, the slipping duration errors are ranged from 7% to 186%. These significant differences are most likely explained by the various fingertip mechanical properties (friction coefficient, hardness, ...). As a consequence, the displacement and the velocity of the string at the release instant will be changed, implying various spectral contents.

The maximal force applied by the finger to the string denoted F_{max} in Tab. III-a) is computed according to the classical plucked string theory [25]. The estimation of F_{max} for the six fingertips is relevant in relation to the value measured on the harpist plucking (about 8.0N) with a maximal average error of 15%, where the reported uncertainty represents a 95% confidence interval. The maximal force, directly induced by the friction coefficient, is related to the dynamics of the produced vibrations. The waveforms of each plucking action presented in Fig. 8 illustrate this remark. For instance, A15O and A5L fingertips convey to the lowest measured maximal forces (5.6N and 6.6N, respectively) and obviously the lowest vibrational magnitude in Fig. 8.

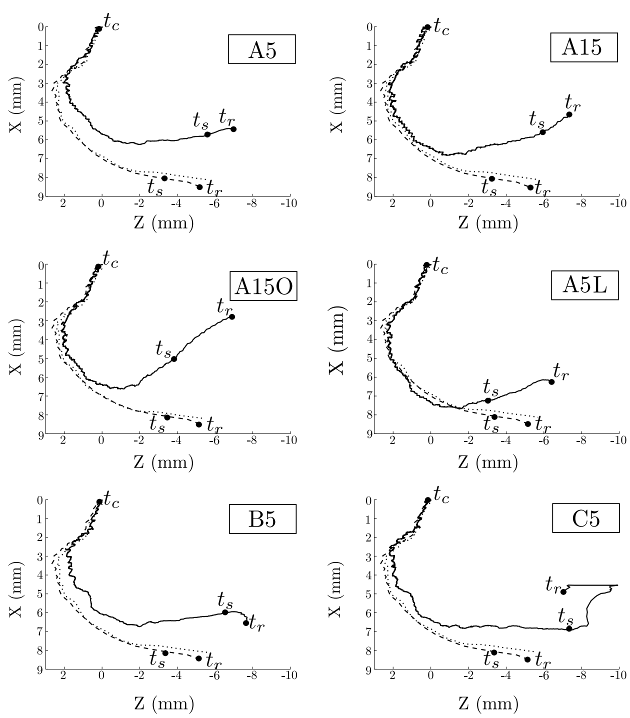

Fig. 7. Comparison of each silicone fingertips trajectory with robotic finger and reference trajectories. Plain line: Silicone fingertip. Dotted line: Robotic finger. Dashed line: Harpist finger trajectory which is defined as reference. t_c, t_s and t_r represent the beginning of the sticking, slipping and vibration phases, respectively.

C. Initial conditions of the string vibrations

The conditions of the string at the release instant define its free oscillations [25], i.e. the soundboard vibrations and the characteristics of the produced sound. Thus, descriptors of the initial conditions of the vibration phase are considered. They are reported in Tab. III-b). The initial displacement of the string at the release instant denoted D is 6.5mm and ranged from 1.0mm to 5.7mm for the reference and the silicone fingertips, respectively. As previously mentioned, this descriptor is related to the slipping duration: during a longer slipping phase, the string will have time to return closer towards its rest position. The initial velocity of the string at the release instant is denoted V in Tab. III-b). As for D, the order of magnitude of V is relevant for the robotic finger with A-shaped fingertip and middle or high hardness. Inconsistency in this descriptor are due to an irrelevant friction coefficient. The more deviated maximal force and slipping duration values are estimated for A15O, A5L and C5 silicone fingertips, which also provide the more erroneous velocity values.

D. Soundboard vibrations

Besides the variations in the silicone fingertip's waveforms magnitude, we observe in Fig. 8 differences of shapes between signals. They seem to be related to the fingertip's geometry. Waveforms obtained within A-shaped fingertips show a similar *wave* pattern just after the maximal magnitude is reached, while the one conveyed by B and C-shaped fingertips have their own particular shapes. Considering vibrations magnitude, the C5 fingertip is the best of the six used. However, regarding the waveform, A15 and A5 fingertips are the closest to the harpist reference.

In order to highlight the best properties providing to a silicone fingertip, we extract and compare characteristic features of these signals [26]. Denoting X the discrete spectrum, of length N, of the soundboard vibrations and f the frequency index function, they are presented in Tab. III-c), and defined as follow:

- P_i measures the amplitude of the i-th peak of the spectrum, in decibel;
- the spectral centroid measures the barycenter of the spectrum: $\mu = \left(\sum_{k=1}^{N} f(k)|X(k)|\right) / \left(\sum_{k=1}^{N}|X(k)|\right)$, in Hertz,
- the central moments of order i=2, i=3 and i=4, defining the spread, the skewness (SK) and the kurtosis (K) of the spectrum are calculated based on the formula $\mu_i = \left(\sum_{k=1}^{N}(f(k)-\mu)^i|X(k)|\right) / \left(\sum_{k=1}^{N}|X(k)|\right)$. SK and K measure its energetic distribution's asymmetry and flatness around its centroid, respectively.

According to results presented in Tab. III-c), notes produced by the 6 silicone fingertips are relevant compared to the reference. The error, averaged on all vibrations descriptors, is ranged from 9.9% to 41.8%. The amplitude and ratio of the spectral peaks are globally well-reproduced while

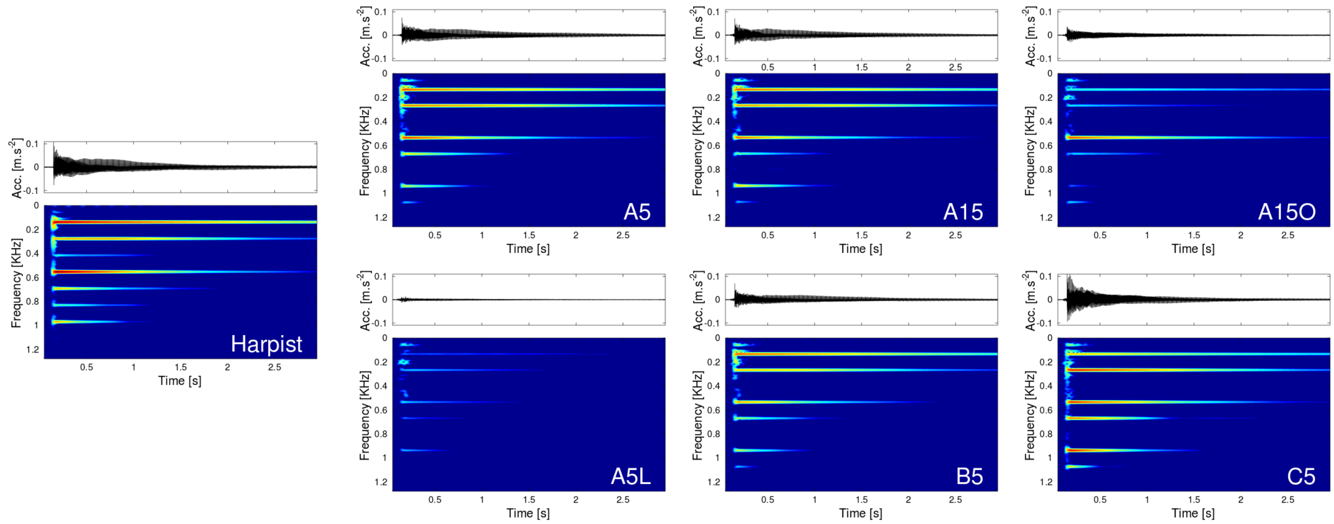

Fig. 8. Waveforms and spectrograms of accelerometer's signals measured on the soundboard at the bottom of the 30th string (D♭2 at 138.6Hz) which is plucked by the harpist and by the robotic finger with each silicone fingertip. Spectrograms are shown in dB using a 70dB dynamic.

TABLE III

CLASSIFICATION OF THE SILICONE FINGERTIPS ACCORDING TO CHARACTERISTIC DESCRIPTORS OF THE PLUCKING ACTION. THE GRAYED-COLORED BOXES CORRESPOND TO THE GLOBAL BETTER FINGERTIPS. THE BOLD VALUES CORRESPOND TO THE CLOSEST SILICONE FINGERTIP TO THE REFERENCE FOR THE CONSIDERED DESCRIPTOR.

a) Plucking action characteristics							
Descriptor	Reference	A5	A15	A15O	A5L	B5	C5
$\Delta\Phi_c$ (ms)	326.6	409.4	408.7	403.5	**402.2**	409.2	409.2
$\Delta\Phi_s$ (ms)	2.8	2.4	**2.6**	5.7	8.0	3.8	4.3
F_{max} (N)	8.0	7.1	7.1	5.6	6.6	**7.6**	9.8
b) Release instant characteristics							
Descriptor	Reference	A5	A15	A15O	A5L	B5	C5
D (mm)	6.5	**5.7**	5.1	3.3	2.2	4.7	1.0
V (m/s)	1.2	**1.19**	**1.19**	0.68	0.92	2.3	0.58
c) Spectral soundboard vibrations descriptors							
Descriptor	Reference	A5	A15	A15O	A5L	B5	C5
P_1 (dB)	68	**64**	63	51	44	**64**	60
P_1/P_2 (dB)	1.1	1.0	1.0	**1.1**	0.94	**1.1**	0.92
P_2/P_4 (dB)	0.91	1.0	**0.98**	0.77	1.0	1.0	1.0
μ (Hz)	722	673	900	1017	**745**	831	1106
σ^2 (kHz)	534	**527**	1117	1081	817	975	1008
SK (-)	2.4	2.6	2.0	1.8	**2.5**	2.1	1.6
K (-)	10.5	11.9	6.7	6.0	**10.0**	7.6	5.5
d) Fingertip classification							
Silicone fingertip		A5	A15	B5	A5L	C5	A15O
Average error compared to the reference		**9.9%**	23.1%	28.2 %	36.7%	41.5%	41.8%

spectral centroid and spectral spread imply error percentage up to 53%. Meaning that, excepted for the A5L finger, the acoustical level and the spectral balance are approximately well-reproduced, but not always as good for the spectral shape.

Moreover, spectrograms of each plucking action have been computed and presented in Fig. 8. Unlike harpist, signals performed by the robotic finger do not contain the 3^{rd} and the 6^{th} harmonics. This difference is due to the plucking position. As the robot was set to pluck exactly the string at the third of its length, the harpist's finger position on the string was prone to slight variations. Furthermore, the transient part, which is essential at a sound perception level, is clearly different from one spectrogram to another. Transient obtained with A5, A15 and C5 fingertips are the closest to the one produced by the real harpist. Again, this phenomenon is the consequence of the various silicone friction coefficients. Finally, as expected, signals resulting from sharp fingertips (B and C shapes) own more energy in high-frequencies than those resulting from smooth fingertips (A-shape) which are closer to the reference spectral energy distribution. Then, adding a glove on the silicone fingertip implies a 30-times reduction of the energy in the signal. Furthermore, considering a same shape, the softer the silicone, the lower the sound radiated energy.

Eventually, according to descriptors presented in Tab. III combined with spectrograms, the isolated notes produced by a part of the set of silicone fingertips is suitable for a harp sound. The silicone fingertip which matches best with the harpist performance is A-shaped and made of silicone with 5% of filler, with an average error percentage of 9.9% regarding to the reference in this study.

VI. CONCLUSION

This paper has presented the development of a repeatable and configurable artificial finger able to pluck a string, especially using a classical harp playing technique. The chosen robot is planar with two rotational joints. It is enhanced by a silicone fingertip. To this end, six silicone fingertips differing on shape and hardness have been molded. The evaluation of the robotic finger is carried out by comparison of its performances with those of a harpist. Using a well-controlled measurement protocol, both plucking action and soundboard vibrations are compared by analyzing plucking action and vibrational features. The robotic finger mostly fulfills repeatability and accuracy objectives relative to the harpist. Concerning the silicone fingertip, one particular shape appears to be relevant over the three tested: cylindrical with round-fingertip. Besides, the silicone's hardness is of great importance since the deformation of the fingertip has an influence on the finger/string friction and the initial conditions of the string free oscillations. According to descriptors of the soundboard vibrations, a middle or high silicone hardness is relevant.

Further works will be carried out to investigate more mechanisms than position control, as for instance force and haptic feedback which are obviously occurring in the harp performance achievement. For this purpose, the fingertip instrumentation is planed. This will be valuable to provide informations about the plucking process to the robotic finger controller.

It will also be interesting to mold fingertips with other materials in order to achieve a thorough study of the finger/string friction characteristic.

Finally this is the first step to a repeatable and configurable excitation system to study string instruments behavior in playing conditions and to point out the influence of musical gesture parameters on the radiated sound.

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