



Effect of plucking dynamics and tonewood on electric guitar tone

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Abstract

The influence of plucking techniques and Tonewood materials on the overall tonal quality of a guitar was determined. Digital waveguide synthesis was used to simulate different plucking techniques and material properties. A consonance-dissonance evaluation method was then used to classify tones as being harmonious and pleasing to the ear (good) or cacophonous (bad). This classification accuracy of this method was verified using blinded listening tests administered to a mixed sample of professional guitarists, amateur musicians and non-musicians. Finally, the results were verified with physical measurements using an actual guitar and a digital audio interface. High-fidelity digital recordings of string vibrations were captured using a Focusrite Solo 4th Gen interface and subsequently analyzed with Audacity[®] software. Pluck forces and pluck angles were quantified with a high-speed video-based method using a slow-motion camera. It was found that tone quality increased as picking width decreased from 0.05 m to 0.01 m. A scaled collision parameter - that served as a surrogate for fretboard stiffness - in the range of 46.5 to 58 N/m, produced a better tone quality, with peaks in tonal quality at specific stiffness values. In addition, different plucking methods significantly affected the tone, with medium force, flat-angled plucking yielding the best results. These results constructed a hitherto unexplored and under-researched understanding of guitar acoustics and may help in material selection for instrument manufacturing as well as in the refinement of the playing technique.

Keywords

Picking techniques, Tonewood, Consonance-dissonance, Guitar acoustics, Digital waveguide synthesis, Harmonic analysis, Material stiffness, Tonal quality, Pluck force, Pluck angle

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Introduction

In the study of musical acoustics, simulations of guitar strings have often focused on creating the best sounds. Consonance–dissonance based methods have been used to quantify the characteristics of "good" and "bad" tone, as discussed by Šali et al. (1), and multiple string simulation models have been developed.

However, despite the detailed simulations and studies of guitars, a quantification of the effects of playing techniques and room properties on tone has been lacking. For example, the technique used to pluck a string, such as fingerstyle versus picking, can have a significant effect on the resulting sound.

The factors influencing the tonal outcome in real-world settings have remained largely unstudied. Previously, a study of picking techniques was summarized by Carral et al. (2). However, this summary only considered the effects of the techniques on the harmonic components of the note, including the fundamental frequency and its overtones, which define the pitch and timbre of the sound. It did not take into consideration the effect of these techniques on the overall quality of tone on the guitar, a broader concept that requires analysis of harmonic components as well as their auditory perception.

This paper aims to address this gap by using a method that integrates simulation techniques developed by Bilbao et al. (3) and the consonance-dissonance method described by Šali et al. (1) to identify how picking methods affect sound quality quantitatively and how

tonewood (the type of wood used for the body, neck, and fretboard of a guitar, influencing the instrument's tonal characteristics) affects sound quality qualitatively.

Methods

General equation

The methodology of Bilbao et al. (3) was followed and key equations from that paper are re-stated. The equations represent the balance of forces acting on the string and the movement of the string over time.

The general equation of motion represents the balance of forces acting on the vibrating string. This balance of forces can be alternatively represented through the action of the differential operator L , and is given by Equation 1, $L = F_e + F_B + F_F + F_{FG}$. Here, L is a differential operator applied to $u(x,t)$, where u is the transverse displacement of the string from its initial position depending on the time and spatial coordinate x of range $[0,D]$ in m and time t in s. In this case, L represents a more general case where external forces influence the string's motion. F_e denotes the plucking excitation force. It can be represented in a Force–Frequency–Gain (FFG) form as $F_e(w) = G_e(w) F_e(t)$ where $G_e(w)$ is the frequency dependent gain factor. The other forces include F_B , the interaction with the fretboard; F_F , the interaction with frets; and F_G , the interaction with the fretting finger.

If no external forces act on the string, the free vibration of the string can be represented by Equation 2,

$$L = \rho A \partial_t^2 u - T^0 \partial_x^2 u + EI \partial_x^4 u + 2\rho A \sigma^0 \partial_t^2 u - 2\rho A \sigma^1 \partial_t \partial_x^2 u \quad (\text{eq.2})$$

Free vibration is encapsulated in $L(u)$. Here, L is purely the intrinsic equation governing the free vibration of the string, without any external disturbances. This describes how the string naturally vibrates after being plucked. ρ is the mass density in kg/m^3 ; T^0 is the tension; E is the Young's modulus; I is the moment of inertia; A is the cross-sectional area; σ^1 and σ^0 are the frequency dependent damping components. All forces are measured in Newtons.

Plucking force

Equation 3,

$$F_e(t) = \begin{cases} f_{amp} \sin^2\left(\frac{\pi(t-t_e)}{2\Delta}\right) & \text{when } t_e \leq t \leq t_e + \Delta, \\ 0 & \text{otherwise} \end{cases}$$

was used to calculate the force $F_e(t)$ applied on the string at a certain point as a function of time. This formula models the initial condition of plucking the string, where t_e is the start time of the pluck, and Δ is the duration of the pluck. It defines the time profile of the plucking force with a \sin^2 shaped curve. A smaller Δ would be anticipated for pick usage while fingerstyle plucking would result in a larger Δ . The plucking force in this model, f_{amp} , is also applied over a range according to the length of the plucking object in contact which is termed as the plucking width.

Fretboard force

Equation 4, $F_b = K_b [b - u]_+^{\alpha_B}$, was used to model the collision of the string with the fretboard, where K_B is the simulated fretboard stiffness parameter. Although K_B is a modelling parameter rather than an actual physical stiffness, it can be used to emulate the relative behaviour of fretboards with varying rigidity. In the formula b represents the smooth profile of the fretboard, and α_B

(the force constant) controls how steeply the force increases with deformation. Here, $[\]_+$ indicates the "positive part of," hence, $[\eta]_+ = (\eta + |\eta|)/2$.

Finger-string interaction

Equation 5, $F_{FG} = -K_{FG} [u(x_{FG}, t) - w(t)]_+^{\alpha_B}$, was used to model the pressing of the finger on the string against the fretboard or frets, where K_{FG} is finger stiffness, $w(t)$ is displacement of the finger over time, x_{FG} is the location of a pluck, and α_B is the stiffness exponent. The equation includes both a collision response and the finger's dynamics. Acceleration of the finger was calculated with Equation 6, $w'' = \frac{F_{FG} + f_{e,FG}}{M_{FG}}$, where M_{FG} is

the mass of the finger. Integrating the right-hand side of Equation 6 twice using the Euler Integration yields the value for w .

Boundary conditions

Equation 7,

$$u(0, t) = \partial_x^2 u(0, t) = u(L, t) = \partial_x^2 u(L, t) = 0,$$

represented boundary conditions. In most models, the output is assumed to be drawn directly from the string displacement at $x = x_0$, such that $y(t) = u(x_0, t)$. However, output in this paper was taken over a 3 cm range at a point where electromagnetic pickups would generally be placed in an electric guitar.

Finger fretting dynamics

Equation 8, $F_F = \sum_{q=1}^M K_F [m_o - u(x_q, t)]_+^{\alpha_F}$, was used to model the interaction of the string with the frets, which protrude above the fretboard, where m_o is the height of the fret above the fretboard and α_F is the fret stiffness exponent ($\alpha \geq 1$). Each fret is treated as a localized barrier at x_q with a stiffness K_F . A nonlinear contact force ensures the

interaction occurs only when the string collides with the fret. Equation 9, $x_q = L \left(1 - 2^{-\frac{q}{12}}\right)$, represents the harmonic distribution of frets on an actual fretboard, where q is the number of frets touching the string.

Numeric stability

Equation 10, $c \frac{dt}{dx} \leq 1$ was used to ensure the stability of the code. This condition is called the Courant condition and ensures stability by requiring that the signal does not move faster than the speed of sound in a given time step.

Consonance-dissonance usage

First, a Fast Fourier Transform (FFT) was performed to convert the time-domain audio data obtained from Audacity® into the frequency domain, revealing the various frequencies present in the signal and their corresponding magnitudes.

Then, these magnitudes were converted to dB(A) weighted values using the conversion graph of dB to dB(A) as for example, in https://www.engineeringtoolbox.com/decibel-d_59.html, which accurately depicts how loudly a human ear, on average, hears different frequencies. Fifteen harmonics were calculated based on the frequency with the highest magnitude using the equation, $f_n = f_{\text{base}} (n + 1)$, (eq.11), where f_{base} is the frequency with the highest magnitude and n is the harmonic number starting from 0.

Next, the harmonic frequencies and their magnitudes were averaged, after the audio was split into 0.2, 0.6 and 1 s after the plucking force terminated. The intervals were also sorted into consonant and dissonant intervals based on Table 1. These intervals

show how the 15 enharmonic components match together. The classification of intervals into consonant and dissonant categories is based on how well their frequencies align. Consonant intervals, such as perfect fifths and major thirds, are characterized by simple frequency ratios, which generally sound stable and pleasant. Sounds containing a larger magnitude of these ratios were termed as good and as “in-tune”. These intervals signify a better tone in a guitar. Dissonant intervals, on the other hand, have more complex frequency ratios which often lead to a perception of instability. Sounds containing a larger magnitude of these ratios were termed as bad and as “out of tune”, similar to Springer et al. (5). The code for the consonance-dissonance use is posted at the Github repository.

Although complex frequency ratios may provide more depth of tone to music, in general usage the harmonic components of a guitar tone are preferred to be in consonant ratios. If an instrument is tuned so that these naturally consonant intervals match the harmonic series as closely as possible, chords and melodies sound more resonant and “in tune” as shown by Bain et al. (6) and Burton et al. (7). The perception test in this study also served to corroborate these findings.

However, this may change for specific genres which require intentional dissonance or microtonal effects, such as jazz, metal, and experimental music. In such cases, tuning and interval choices may deliberately deviate from simple harmonic ratios to create tension, colour, or a unique tonal character. Hence, this study pertains to general enhancement of clarity and perception of being in-tune. Therefore, whenever a tone is termed as

being ‘better’ in this study, it is in terms of being in tune of the tone, compared to the the general clarity and the perception of it dissonant tone.

Table 1. Classification of intervals into consonant and dissonant, showing how each interval was used in the calculations

Consonant Frequency Ratios	<i>i</i>	<i>j</i>	Consonant Frequency Ratios	<i>i</i>	<i>j</i>	Dissonant Frequency Ratios	<i>i</i>	<i>j</i>
<i>octave</i>	2	1	<i>major sixth</i>	5	3	<i>minor sixth</i>	8	5
	4	2		10	6	<i>minor third</i>	6	5
	6	3		15	9	<i>minor seventh</i>	9	5
	8	4	<i>major third</i>	5	4	<i>major tone</i>	9	8
	10	5		10	8	<i>major seventh</i>	15	8
	12	6		15	12	<i>"octave"</i>	14	7
<i>perfect fifth</i>	3	2	<i>perfect fourth</i>	4	3			
	6	4		8	6			
	9	6		12	9			
	12	8						

Equation 12, $L_{ij}(k) = 10 \log \left(10^{\frac{L_i(k)}{10}} + 10^{\frac{L_j(k)}{10}} \right)$, depicts the Sound Pressure Level (SPL) of the intervals, where $L_j(k)$ and $L_i(k)$ represent the A-weighted SPL for the two frequencies which are part of the interval and k refers to

the specific overtone of the assumed good or bad note being calculated.

The formula for $\Delta L_{ij}(k)$ was calculated for both types of the sound notes. A good and bad note were assumed and then $L_{ij}(k)$ was subtracted.

$$\Delta L_{ij}(k) = L_{ij}(k) (k : \text{assumed good}) - L_{ij}(k) (k : \text{assumed bad}) \quad (\text{eq.13})$$

This calculation was performed for all of the ratios mentioned. $\Delta L_{ij}(k)$ for consonant and dissonant ratios were sorted into different categories. The sum of negative and dissonant $\Delta L_{ij}(k)$ was sorted into $D_B(k)$, the sum of positive and dissonant $\Delta L_{ij}(k)$ was sorted into a category termed $D_G(k)$, and the same process was performed for positive and consonant $\Delta L_{ij}(k)$ in $C_G(k)$ and negative and consonant tones in $C_B(k)$, as shown in Equation 14.

$$Q(k) = D_G(k) + D_B(k) - C_G(k) - C_B(k) \quad (\text{eq.14}).$$

If the $Q(k)$ was negative, the assumed bad tone was considered tonally worse than the assumed good tone. A positive $Q(k)$ indicated

a better quality of the assumed bad tone in comparison to the good tone.

With this logic, different $Q(k)$ values were compared to the same tone. If one $Q(k)$ was larger than another $Q(k)$ being compared to the same assumed good tone it meant that the larger $Q(k)$ value could be implied to be a better tone.

Verification of tone perception via listening tests

To validate the perceptual relevance of the $Q(k)$ measurements, a blinded listening test

was conducted with 27 participants divided into three groups, 1] Professional Guitarists consisting of 9 individuals with at least 5 years of active guitar performance experience, 2] Amateur Musicians consisting of 9 participants with formal musical training on other instruments or general music experience, but limited guitar experience and 3] Non-Musicians consisting of 9 participants with no formal musical training or experience.

Each participant was presented with randomized pairs of audio recordings representing different pluck forces and picking methods. They were asked to select which recording in each pair they perceived as having a “better” or “preferred” tone, without knowledge of the experimental conditions. Participants were asked to wear headphones and to sit in a quiet environment while taking the listening test. 3 sets of 3 different notes with different $Q(k)$ values were played for each of the participants. The participants arranged the three notes in order of which sounded better.

Responses were then compared to the $Q(k)$ values from the recordings. Alignment with $Q(k)$ rankings for all 3 sets was observed in 8 of the 9 cases for professional guitarists, 7 of the 9 for amateur musicians, and 5 of the 9 cases for non-musicians. The remaining participants were able to rank at least 1 or 2 sets correctly. These results indicated that the $Q(k)$ analysis correlated with listener-perceived tonal quality, especially for participants with musical experience, while still capturing perceptual differences noticeable to non-musicians.

Physical measurement

Equipment

The equipment used for the experiment consisted of 1] A Focusrite Scarlett 4th gen solo, which is an audio interface to read in the analog signal and convert it to a digital one within the computer, 2] A Fender Stratocaster with standard pickups (neck single coil selected) (guitar neck of rosewood for set 1 and Maplewood for set 2), 3] A 3-metre fender guitar cable, 4] Audacity[®], a free audio-editing software, 5] Slow motion camera at 240 fps and 6] A measurement scale.

Methods

The guitar was connected directly using a 3-meter Fender guitar cable to the Focusrite Solo 4th Gen interface, with the sampling rate set at 44.1 kHz and 24-bit resolution to capture high-fidelity digital recordings of string vibrations. The experiment was conducted in a soundproofed room, minimizing external noise and ensuring a controlled acoustic environment. The room had balanced reflections, with walls and surfaces designed to prevent unwanted reverberation or standing waves.

The conditions set for the experiment were Room temperature = $22 \pm 1^\circ\text{C}$ and RH = $45 \pm 3\%$. Audacity[®] was used to record the audio. Three measurements were recorded for three pluck forces — small (~ 0.7 N), medium (~ 1.8 N), and large (~ 3.5 N) — for each of the four picking methods: angled pick 45°, straight pick, fingerstyle without nail, and fingerstyle with nail. The force measurement procedure is described in detail later.

The values for small, medium, and large pluck forces were chosen based on measurements of typical playing forces by

three experienced guitarists, where gentle finger plucks averaged 0.5–1.0 N, moderate pick attacks averaged 1.5–2.0 N, and aggressive pick strokes occasionally reached 3.2–3.5 N. The experimental setup ensured minimal extraneous noise, with the guitar placed on a stable stand and consistent posture and plucking technique maintained. The angles for all plucking methods were confirmed through camera measurements.

The measurements were repeated four times on two separate days. The strings on the

guitar were replaced between days. A second set of experiments was performed with a maplewood neck in the same manner as the first set. Comparative analysis of the sound files was performed using the Q(k) method, comparing the tones to the flat-faced pick, medium-force recording from the first experiment. The results are presented in Table 2 for the rosewood guitar and in Table 3 for the maplewood guitar. Error bars for the rosewood guitar neck are shown in Figure 1, and those for the maple wood neck are shown in Figure 2.

Table 2. Relationship of Q(k) to plucking method and force on rosewood guitar neck

Experiment 1	Low force $\approx .7\text{N}$ (Q(k))	Medium force $\approx 1.8\text{N}$	High force $\approx 3.5\text{N}$
Flat-faced Pick	-47.2	0	-19.6
Angled pick	-40.8	-19.4	-25.5
Fingerstyle w/ nail	-58.9	-27.4	-32.6
Fingerstyle w/o nail	-101.5	-30.6	-48.9
Experiment 2			
Flat-faced Pick	-48.7	0.3	-18.2
Angled pick	-41.1	-19.2	-27.2
Fingerstyle w/ nail	-52.6	-25.8	-34.5
Fingerstyle w/o nail	-107	-31.4	-45.7
Experiment 3			
Flat-faced Pick	-48	1	-19
Angled pick	-40	-26.4	-26.4
Fingerstyle w/ nail	-58	-28.1	-31.2
Fingerstyle w/o nail	-100	-39	-47.5
Experiment 4			
Flat-faced Pick	-48.3	-1	-18
Angled pick	-42	-19	-27
Fingerstyle w/ nail	-54.2	-26.5	-33
Fingerstyle w/o nail	-108.6	-33	-46.1

Table 3. Relationship of Q(k) to plucking method and force on maplewood guitar neck

Experiment 1	Low force $\approx .7\text{N}$ (Q(k))	Medium force $\approx 1.8\text{N}$	High force $\approx 3.5\text{N}$
Flat-faced Pick	-40.6	6.28	-8.8
Angled pick	-34.4	-14.2	-18.5
Fingerstyle w/ nail	-51.3	-20.8	-27
Fingerstyle w/o nail	-94.6	-24	-42
Experiment 2			
Flat-faced Pick	-42.4	6.7	-12.3

Angled pick	-35.6	-13	-22
Fingerstyle w/ nail	-45.9	-19.5	-28
Fingerstyle w/o nail	-101	-24	-38.9
Experiment 3			
Flat-faced Pick	-41	6	-13
Angled pick	-34.9	-21	-23
Fingerstyle w/ nail	-51	-21	-29
Fingerstyle w/o nail	-94/2	-33	-42.1
Experiment 4			
Flat-faced Pick	-43	5	-12.5
Angled pick	-35	-13	-20.3
Fingerstyle w/ nail	-47.8	-21	-26.3
Fingerstyle w/o nail	-102	-27.2	-40.5

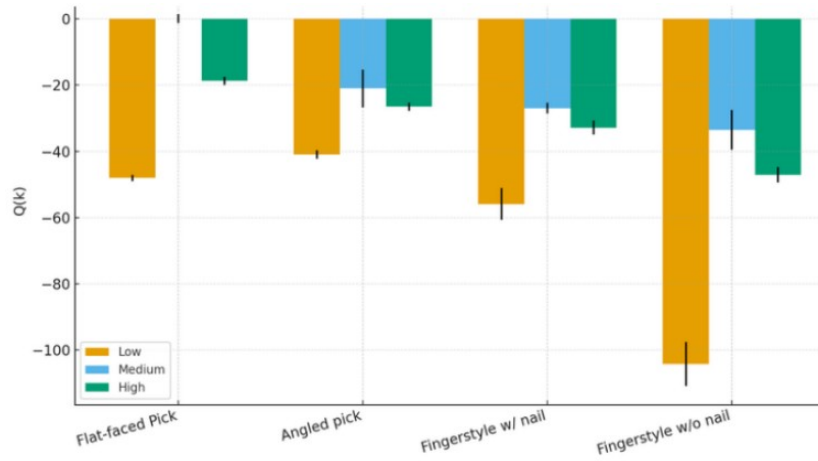


Figure 1. Relationship of Q(k) to plucking method and force on rosewood guitar neck. The Mean Q(k) with 95% CI by method and force is shown.

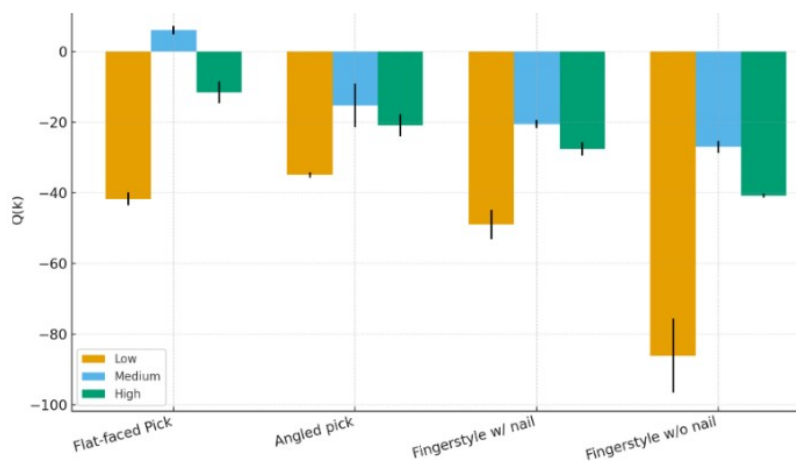


Figure 2. Relationship of Q(k) to plucking method and force on Maplewood guitar neck. The Mean Q(k) with 95% CI by method and force is shown.

Force measurement

Pluck forces were quantified using a high-speed video-based method. A slow-motion camera recording at 240 fps captured the motion of the string immediately after plucking. Force was calculated by analyzing the string's displacement, velocity, and acceleration frame by frame, in conjunction with the known string mass and stiffness, as well as the estimated mass of the force application unit (finger = 25 g, fingernail = 0.025 g, or pick (0.73 mm) = 0.6 g).

Prior to performing the experiments, calibration was performed using a preliminary lever setup as described in Šali et al. (1). Three blocks of known weight (80 g, 150 g, 360 g) were used to apply a nominal force to the string. The resulting string motion, recorded by the camera, was used to verify that the force calculated from video

analysis of each block matched the applied weight within ± 0.05 N, demonstrating the reproducibility of this technique.

Repeated measurements of all forces obtained a standard deviation of 0.04 N. This consistency was observed across all methods, over two separate days, and on both rosewood and maplewood guitars. The resolution of the measurement system was ~ 0.05 N, and the system's sensitivity was also 0.05 N. This method ensured the accuracy and reproducibility of pluck forces across all plucking conditions, sessions, and instruments, thus enabling accurate comparisons of tonal measurements.

Simulation

A list of constants used for simulations can be found in Table 4.

Table 4. Variables and general values used to generate the .WAV file

Variable	Value
Pluck width	0.025m
fretboard position	-0.002m
fretboard stiffness	58.9N/m (reflecting the simulation parameters; not the real material stiffness)
E (youngs modulus for string)	2.0×10^{11} Pa
R (string radius)	0.000364 m
Pluck start time	0s
Pluck time length	0.2s
String length	0.65m
Finger mass*	0.05kg
Fret stiffness	589 N/m
Collection width	.03m
Pluck force	1.8N

*Represents the total apparent mass of the fretting finger pressing on the string in the simulation. The mass listed in the 'Force Measurement' section (25 g) was used in the calculations for that section.

Multicollinearity analysis

A multicollinearity analysis (Table 5) was performed to assess the presence of a

correlation between the magnitude of force and the type of plucking method. All Variance Inflation Factor (VIF) values were < 3 ,

indicating that multicollinearity did not occur to any significant extent.

Table 5. Multicollinearity analysis of force and plucking techniques

Technique	R ²	Variance Inflation Factor (VIF) = 1/(1-R ²)
Angled pick	0.64	2.78
Flat-faced pick	0.60	2.50
Finger w/ nail	0.61	2.56
Finger w/o nail	0.58	2.38

Multicollinearity was also assessed for the simulation model, where the variables were designed to be independent. To confirm this, pairwise VIF was computed for all variables whose impact on Q(k) values was assessed. All VIF values were < 3, confirming the absence of multicollinearity. Thus, each variable contributed independently to the analysis and that any observed effects on the outcome were not confounded by relationships between predictors.

Results

The tonal differences between various playing techniques and material properties were evaluated by computing Q(k) values. This section presents the results of this analysis, highlighting key trends and correlations between plucking dynamics, fretboard stiffness, and the perceived quality of tone.

ANOVA analysis was first performed on the experimental data, subsequent to performing the Levine's test for homoskedasticity. For experimental data, the results demonstrated that picking method significantly affected the Q(k) values ($p < 0.001$ at all force levels). The two values in the parenthesis (Tables 6 and 7) represent between-group degrees of freedom and within-group degrees of freedom respectively.

These results also showed that the type of fretboard used was not significant in affecting tonal quality. However, the mean Q(k) values for the different fretboards showed consistent; albeit small; differences, suggesting that while fretboard type did not strongly determine tonal quality, it may still contribute subtle changes in tone that could be perceptible in practice.

Table 6. ANOVA analysis of experimental forces

Factor	F Value	P Value	ANOVA type after Levene's test
Force strength	F(2,45) = 23.88	8.56 x 10 ⁻⁸	One-way ANOVA
Picking method	F(3, 6.8) = 18.2	1.2 x 10 ⁻⁴	Welch's ANOVA
Fretboard type	F(1, 94) = 1.464	0.229	One-way ANOVA

Three groups (low, medium and high) were compared for Force strength. The Picking method compared four groups (flat-faced pick, angled pick, fingerstyle with nail and fingerstyle without nail). The Fretboard type compared two groups (rosewood and maplewood). The two values in the brackets indicate between group degrees of freedom and within group degrees of freedom respectively.

Table 7. ANOVA analysis of simulated results. The two values in the brackets indicate between group degrees of freedom and within group degrees of freedom respectively.

Factor	F Value	P Value	ANOVA type after Levene's test
Force	F(1,39) = 168.85	4.3×10^{-21}	One way ANOVA
Force (3 groups)	F(2,45) = 34.3	5.77×10^{-12}	One way ANOVA
Plucking location	F(1, 59) = 18.98	1.62×10^{-5}	One way ANOVA
Material stiffness	F(2,40.3) = 85.4	2.1×10^{-21}	Welch's ANOVA
Material stiffness (47-50N/m)	F(1,15) = 2	0.17	One way ANOVA
Plucking time	F(1,78) = 11.96	1.91×10^{-4}	One way ANOVA
Plucking width	F(1,20) = 22.21	3.39×10^{-6}	One way ANOVA

The two groups for Force were (low and high). The three groups for Force (second row) were (low, medium and high). Groups for Plucking location were (near bridge and near neck). Groups for Material stiffness were (low, medium and high). Groups for Material stiffness (47-50N/m) were the stiffness parameters representing those of rosewood and maplewood. The groups for Plucking time were (short and long) and the groups for Plucking width were (narrow and wide).

The analysis shows that, after an initial spike, increasing force modestly worsens the quality of tone beyond 3.2N, as shown in Figure 3. This observation is also supported by the recorded physical measurements presented in

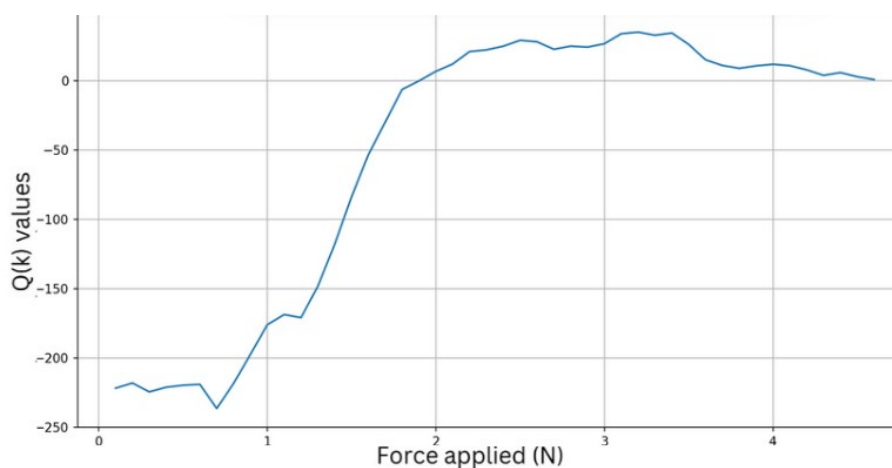


Figure 3. Q(k) vs force applied. This graph highlights the importance of force in producing the tone of the guitar with better tone when harmonics are excited but worse tone with larger force causing detuning.

The ANOVA results presented in Table 7 p-values for physical and simulated experiments indicate that force has a highly significant effect on Q(k). The discrepancy between the measurements include slight variability, such

as sensor noise, small differences in pluck technique, and material inhomogeneities. Additionally, the simulated analysis used a continuous force range of 0–4 N, whereas the physical data are grouped into three discrete levels: low (0.7 N), medium (1.8 N), and high (3.5 N). Grouping increased the within-group variance and reduced the F-value. When ranges similar to those used in the experimental tests are considered, the ANOVA results aligned closely with the experimental ANOVA results shown in Table

7 (Force, 3 groups and Material stiffness (47–50 N/m)), whose F ratios of 34.3 and 2.0 are consistent with their counterparts in Table 6 (23.88 and 1.464 respectively).

An oscillation pattern was also observed, which may indicate that specific displacements improve the enharmonic components. However, this effect is unlikely to be exploitable in regular playing, as it would require extremely precise string placing and displacements.

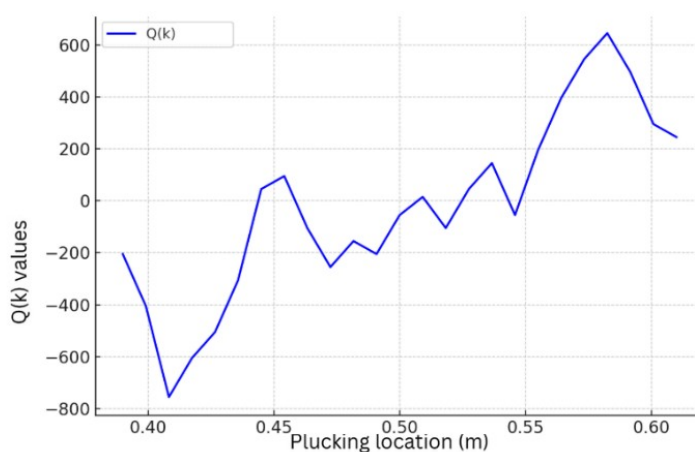


Figure 4. $Q(k)$ vs Plucking Location. This graph highlights the importance of the plucking location showing guitar tone sounding better near the bridge. The peaks and nadirs imply the respective gain and loss of tonal performance at specific nodes.

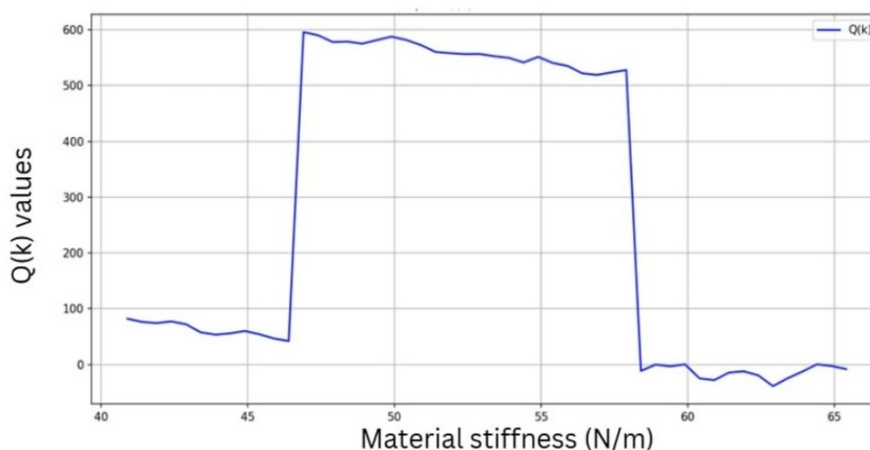


Figure 5. $Q(k)$ vs Fretboard Stiffness. This graph highlights how different Tonewood's for fretboards affect the tone with change in stiffness with the range simulation stiffness values of 46.5 to 58 N/m yielding the best tone.

With respect to plucking location, it was determined that the tone improved as the plucking point approached the bridge of the guitar, as shown in Figure 4. The oscillation is due to the increase in the number of harmonics near the bridge, caused by nodes and antinodes, as demonstrated in Campbell et al. (4) and Carral et al. (2). This is also consistent with data reported by Caroline et al. (8), who showed that plucking closer to the bridge produces a brighter tone. The ANOVA for plucking location in Table 7 indicated a highly significant effect of location on $Q(k)$.

Regarding the effect of fretboard material stiffness on tone, Figure 5 shows the $Q(k)$ values as a function of material stiffness. Fretboard stiffnesses between 47 and 57 N/m (simulation parameter reflecting tonal trends, not exact structural stiffness) produced a better tone, as indicated by higher $Q(k)$ values in this range.

A fretboard that is too soft (lower stiffness) may absorb energy more easily from the string, leading to a dull tone, while a fretboard that is too hard may excessively

reflect vibrations, causing an uneven frequency response. In this case, different resonant absorptions for various stiffnesses may also contribute to the oscillating pattern shown in Figure 5, indicating that material differences affect the measurements. With a more accurate diagram and further study, the simulation stiffness values could be converted to actual material stiffness values to optimize guitar materials for cost and tonal quality. The physical study also indicated that maplewood, on average, produced a slightly better tone than rosewood. However, since the p-value shown in Table 2 is 0.229, this effect appeared non-significant.

For material stiffness, the ANOVA results in Table 7 indicated a highly significant effect on $Q(k)$, showing that stiffness strongly affected tonal response. When ANOVA was applied over a narrower stiffness range, similar to that experienced between maplewood and rosewood, the effect was smaller and consistent with experimental verification, suggesting noticeable but minimal tonal differences within this limited stiffness range.

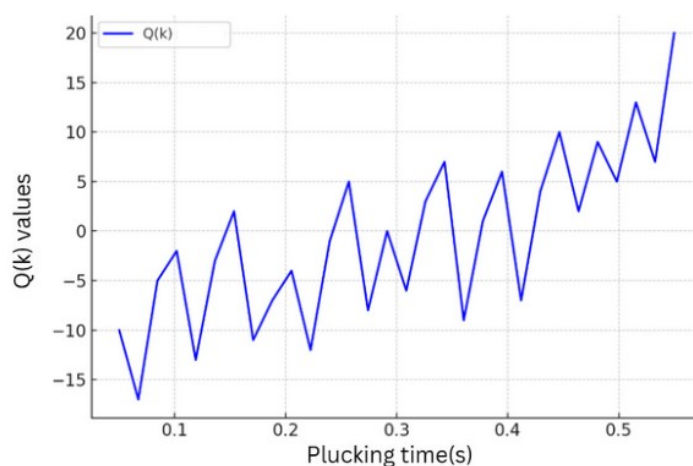


Figure 6. $Q(k)$ vs Plucking time. This graph highlights how different plucking times may cause different tones depending on whether the string is excited to the right point to produce harmonics pertaining to those notes.

The oscillation in $Q(k)$ values with pluck time, shown in Figure 6, indicated that increased plucking duration slightly correlated with better tone. However, compared to Figure 3, where plucking force was varied, the pattern was more oscillatory and less direct. The ANOVA for plucking time depicted in Table 7 showed a significant effect of timing on $Q(k)$.

Figure 7 shows that at plucking width values > 0.01 m, decreasing the plucking width increases the quality of the tone. However, for widths less than 0.01 m, tonal quality is severely compromised. This result is

consistent with Wiciak et al. (9). This indicates that the optimal picking width is 0.01 m and increasing or decreasing the plucking width from this optimal value will cause the tone to worsen.

The ANOVA for plucking width in Table 7 indicated a significant effect, confirming that plucking width influenced tonal quality. It should be noted that work by other authors (10) using the Karplus-Strong method, instead of Fourier-domain time difference analysis, also shows similar trends, thereby corroborating this analysis.

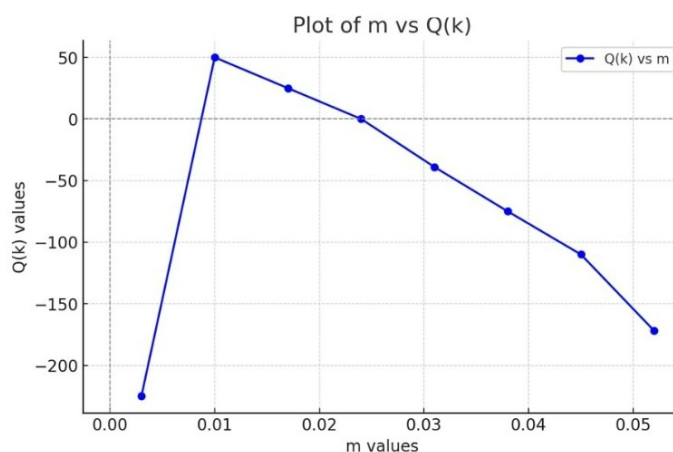


Figure 7. Relationship of $Q(k)$ to plucking width. This figure highlights how smaller plucking width causes better tones until about .01m when tone starts to worsen.

Discussion

In this paper, simulations were performed to investigate the impact of pick angle, pick width, tonewood, picking force, and picking location on tone quality. From Figure 7 and Tables 2 and 3, it is evident that a flat-angled pick produces the best tone, while an angled pick results in a poorer tone. The tone from fingerstyle plucking was also found to be worse than flat picking, as shown in tables 2 and 3. Measurements of plucking force and

duration further revealed how different forces excite harmonics differently.

In addition, these findings suggest that a guitar string has specific points where the tone is better. These points can be used for designing improved guitars by employing optimization techniques to identify materials that provide the best overall tone. This method can also be used to create guitars with optimal picking locations, aligning with the areas where a player would usually pick.

Furthermore, although the difference in tone between maple wood and rosewood was minimal, guitar luthiers could utilize the findings of this study to improve their instruments. By aging the guitar to a specific stiffness, luthiers could achieve stiffnesses that provide the best tones without sacrificing player comfort or altering finger-material interaction, by aligning with the points identified in an optimized version in Figure 5.

This study did not fully address variations in tone preferences across different playing styles and musical genres. Although it provided a general framework for identifying better tone, it did not consider the subtle genre-specific preferences of guitar performance, which may require further investigation.

Jarl et al. (11), Shea et al. (12), and Sutar et al. (13) demonstrated that listeners in specific genres, such as metal and jazz, preferred tones with less emphasis on purely consonant harmonics, instead favouring richer dissonances, microtonal nuances, or aggressive overtones. Additionally, although aligning plucking angles and positions to emphasize consonant harmonics improved perceived tonal clarity in a general context, these results may not directly translate to all genres.

Similarly, Eerola et al. (14) highlighted that the perceptions of consonance and dissonance were context-dependent, consistent with the limitations of this study. However, for general tuning and usage, as shown in Bain et al. (6) and Burton et al. (7), as well as in the tonal perception tests performed in this study, these results can be applied in most scenarios to achieve an improved tone.

This model can also be extrapolated to serve as a tuning system for other instruments. With sufficient research on harmonic content, instrument-specific resonances, and perceptual preferences, it could guide the design of tuning schemes that optimize consonance and overall tonal quality across a variety of instruments.

While this study provides valuable insights into guitar tone, future work could include a broader range of instruments, increased sample sizes for Tonewood comparisons, and analysis across multiple musical genres to enhance generalizability.

Limitations

There were several methodological constraints which were not considered in this study. The estimated 0.05 N force resolution from 240 fps video is likely optimistic, and tonal weighting, harmonic interval assumptions, and the choice of a “good” reference is subjective. The robustness to pickup choice, guitar model, and room acoustics were not assessed, and $Q(k)$ depends on the chosen reference. No mechanical plucking or control recordings were used, and pickup/cable/interface frequency response, output level normalization, and hand-placement effects had no clear corrections. A-weighting was also applied without level matching, and string age was reset between days, but material inhomogeneity corrections were not described.

Additionally, although the results indicate that material stiffness could slightly impact tone, this study did not incorporate other factors influencing the tone, such as player

comfort and finger-material interaction, which may affect overall playability.

Future research could build upon these findings by conducting a survey of guitarists' most comfortable picking positions. This would enable optimization of material stiffness for guitar fretboards to improve both tone quality and playability.

Conclusion

It was found that tone quality increased as picking width decreased from 0.05 m to 0.01 m. Tone quality worsened below 0.01 m. It was also found that a fretboard stiffness in the range of 46.5 to 58 N/m - a scaled collision parameter reflecting tonal trends rather than a physical material stiffness - produced better

tone quality. Additional results indicated the influence of excitation force strength, plucking location, and plucking timing on overall tone. These results provided insight into different plucking methods as well as the effects of various fretboard materials on the overall tonal quality.

Based on the findings of this study, it can be concluded that certain picking methods generally produce better tone than others. Although individual picking methods may have specialized uses for specific playing styles, this paper provides a systematic classification of fretboard materials and plucking dynamics that generally enhance tonal quality.

Data repository

<https://github.com/raynolm/Q-k-consonance-dissonance-Usage-code>

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