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Impact of vertical vibrations on human rhythmic jumping

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ABSTRACT

This paper investigates the human ability to perform rhythmic jumping on a vertically vibrating platform by analysing kinetics and kinematics. Ten test subjects participated, performing jumping on both non-vibrating and vibrating platforms. Vibration frequencies of 2.0, 2.4, and 2.8 Hz were used, with a vibration level of 2 m/s^2. The frequency of jumping matched the vibration frequency, and for the first time, the jumps were timed relative to the platform's position in the vibration cycle. A metronome prompted landings at four target positions: (i) reference position and on the way down (mid-down), (ii) lowest position (trough), (iii) reference position and on the way up (mid-up), and (iv) highest position (peak), at each frequency. The study compared the achievement of the target frequency of jumping between non-vibrating and vibrating platform conditions for each frequency. Results showed the worst performance when the target frequency was 2.8 Hz on the non-vibrating platform, confirming the difficulty of faster jumping on non-vibrating surfaces. The discrete relative phase analysis revealed a preference for landing at the trough and mid-up positions on the vibrating platform, particularly at 2.8 Hz. The preferred timing of jumps corresponded to greater toe clearance and impact ratio, but shorter contact duration compared to the non-vibrating platform. These findings hold promise for improving human-structure interaction models for assembly structures used in sports and musical events.

1. Introduction

Crowds of people jumping rhythmically during sports or music events or while exercising can impart large dynamic forces on grandstands and floors. Rhythmic jumping is primarily characterised by a repeated alternation between contact and flight phases at a given frequency. The achievable frequencies of rhythmic jumping range from 1.0 to 4.0 Hz [1–5]. When the frequency of rhythmic jumping or one of its integer multiples matches one of the natural frequencies of the structure, it causes resonance and results in potentially excessive structural vibrations. The peak force generated by rhythmic jumping is approximately 2.0–4.0 times larger than the jumper's body weight (*W*) [1]. When a person performs bobbing, an activity that mimics jumping while always maintaining contact with the ground, the peak force is between 1.3 *W* and 2.5 *W* [1]. These ranges are 2.0–2.9 *W* and 1.0–1.5 *W*, for running and walking, respectively [6]. Therefore, a single individual generates the largest dynamic force while jumping rhythmically. This can cause serious consequences, especially when performed by crowds. Recently, a single person caused the collapse of a crowded footbridge in Cuernavaca, Mexico by jumping on it during its opening ceremony injuring at least 25 people [7]. Another example of structural damage caused by large groups of people jumping was the partial collapse of a football stadium in the Netherlands amid crowd celebrations mimicking players jumping in celebration on the pitch [8]. This is the reason to investigate the rhythmic jumping in this paper.

The vibration of the supporting structure could force the rhythmic jumper to adjust their body movement to the structural motion, altering the previously expected structural vibration response and the properties of the dynamic system. These mutual and continuously evolving influences of the structure on the human and vice versa are collectively referred to as human-structure interaction (HSI). Studying HSI requires an understanding of both structure-to-human interaction (S2HI), whereby vibration of the supporting structure forces adaptation of human kinematics and resulting kinetics, and human-to-structure interaction (H2SI), whereby the human presence and their actions influence the structural dynamics and vibration response. Besides their contribution towards the total HSI, S2HI and H2SI are significant on their own in certain situations. An example of the S2HI–only scenario would be a person jumping on a structure that was already excited by another source (such as other people, wind, or equipment), while an

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example of the H2SI–only scenario would be when a largely vibration-insensitive person is jumping on a structure. While the latter can be considered a rare event, the former cannot be disregarded. For example, S2HI occurs when a person or a group of people attempts to jump on a grandstand excited by an active crowd or a lively footbridge excited by the wind or performs aerobics on a floor excited due to others exercising.

The first measurements of human-induced dynamic forces due to jumping on perceptibly vibrating structures were made by Yao et al. [5,9]. They concluded that it is impossible to jump at exactly the structure's natural frequency. A jumper achieved only 1.8 Hz while attempting to jump at 2 Hz on a test rig with the natural frequency adjusted at either 2 Hz or 4 Hz and with a jumper-to-platform mass ratio (MR) of 0.42. The modal acceleration was between 1.5 and 2.2 *g*, and therefore extremely large. Similar results were obtained for jumping at 2.5, 3.0 and 3.5 Hz which caused near-resonance excitation. Furthermore, the contact ratio was always greater than 0.5 and approached 1.0 near resonance indicating a low-impact jumping.

Harrison et al. [10] conducted a comparative study on the same rig using a test configuration with an MR of 0.21 in addition to Yao et al.'s configuration with an MR of 0.42 [5]. This study revealed the ability to jump at the frequency of the rig, i.e., in resonance, when the MR was 0.21, in contrast to the inability to do so when the MR was 0.42. This is due to the reduced levels of structural response at the lower MR. The maximum modal acceleration was 2.2 *g* for the cases with MR = 0.42 compared to 1.8 *g* for those with MR = 0.21. They also observed a reduction in the magnitude of the first forcing harmonic generated while jumping near and at resonance in comparison with the force recorded in nominally the same tests on a rigid platform. The minimum force reduction of 35% was observed for a case with a maximum acceleration of 1.2 *g*, whilst the maximum force reduction was 50% for a configuration that had a maximum acceleration of 1.5 *g*. Therefore, a greater reduction in force is to be expected when the response levels are higher owing to the HSI. They claimed that the consideration of HSI resulting in the force reduction could lead to a reduction of DLFs used in performance–based calculations, thus lowering the calculated response.

A study by White et al. [11] showed that it is possible to jump rhythmically in resonance at lower jump heights while it becomes impossible to do so at greater heights. This is due to inconsistent jump height and short-lived and large contact forces during landing from a high jump while the ground moves up towards the jumper. As a result, rhythmic jumping becomes physically inadmissible and might lead to serious injury.

White et al. [12] conducted tests involving rhythmic jumping on a flexible timber beam with a natural frequency of 1.89 Hz. Their study examined the force-displacement relationship during rhythmic jumping at frequencies ranging from 1.05 to 3.45 Hz in intervals of 0.15 Hz. The researchers observed that as the frequency of jumping increased, the leg compressed less while the peak contact forces increased, resulting in an apparent increase in leg stiffness. By comparing the stiffness observed during jumping on the beam with that on a non-vibrating surface, the authors concluded that the human body adjusts its apparent stiffness to accommodate different surface stiffness levels, enabling sustained rhythmic jumping. In addition, they observed an 'antiphase' behaviour between the jumper and the beam at higher frequencies and an 'in–phase' behaviour at lower frequencies. However, there was no quantification or further exploration of this tendency.

In summary, previous research indicates that significant vibrations produced during jumping at resonance have the greatest potential to impact the jumping action. However, there is limited literature [12] that specifically examines the influence of the frequency of jumping on vibration-jumper dynamics. Additionally, the extent to which jumpers adapt their body movements to the structural motion remains largely unknown. For instance, it would be intriguing to investigate whether there is a preference for a specific time instance in the vibration cycle when the jumper lands on the structure.

In this study, tests were devised to collect vertical ground reaction force (GRF), and displacements of landmark locations on the jumper's body and the platform to analyse the S2HI. A metronome was used to guide the TSs to jump at a frequency that was the same as the frequency of the vertically vibrating platform and to land at specific platform positions in each vibration cycle. Human kinematics, kinetics and subjective rating of vibration were recorded. Kinematic and kinetic data from the non-vibrating surface were used as the benchmark.

This paper consists of five sections. After this introductory section, Section 2 describes the test protocol and data management. The methodology used to extract jump parameters from the data is detailed in Section 3. Section 4 presents the analysis of the jumping action on the platform, the results, and the discussion. The conclusions are presented in Section 5.

2. Data collection

Tests were conducted in the VSimulators facility [13] at the University of Exeter to collect kinetic and kinematic data for individuals jumping rhythmically on the vibrating and non-vibrating platforms. The test protocol was approved by the Research Ethics and Governance team of the University of Exeter.

2.1. Test setup

The VSimulators is a motion platform equipped with nine large AMTI BP12001200 force plates [14], embedded in the floor to measure the ground reaction force (GRF) at a sampling rate of 1000 Hz. Each force plate had a size of 1.2 m × 1.2 m and a capacity of 8.9 kN. In addition, an OptiTrack motion capture system [15], consisting of 16 OptiTrack Prime 13 cameras, was used to track trajectories of reflective markers attached to the human anatomical landmarks while moving in the capture volume of the VSimulators. The sampling rate of this system was 100 Hz. The conventional full-body marker set comprising 39 markers was adopted [15]. Additionally, four markers were placed at the four corners of the platform.

Test participants were invited from the student and staff population at the University of Exeter. The participants were selected on a first-come, first-served basis, with slightly different considerations for males and females. Six male and four female healthy TSs provided written informed consent and participated in the study. The TSs confirmed that they were:

(i) over 18 years of age,
(ii) not prone to motion sickness/vibration sensitivity, and
(iii) not suffering from locomotion impairments.

Additionally, pregnancy was an exclusion criterion for the female TSs. The anthropometric details of the TSs are listed in Table 1.

The TSs wore a motion capture suit to which the reflective markers

Table 1
Anthropometric data of test subjects (TSs).

TS #	Age [years]	Gender(F-female, M−male)	Height [cm]	Body mass [kg]
TS01	26	F	164	54.6
TS02	30	F	164	53.5
TS03	27	M	169	65.6
TS04	24	M	182	65.8
TS05	28	M	172	63.1
TS06	23	M	170	58.8
TS07	33	M	172	77.0
TS08	20	M	175	64.5
TS09	21	F	161	56.0
TS10	23	F	168	70.7

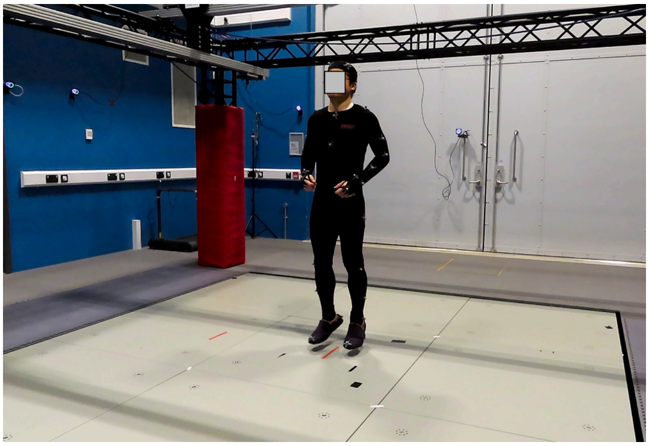

Fig. 1. TS jumping on the VSimulators platform.

were attached. A fully instrumented TS jumping on the VSimulators platform is shown in Fig. 1.

2.2. Test configurations

The TSs were asked to jump at 2.0, 2.4, and 2.8 Hz prompted by the metronome under vibrating and non-vibrating conditions of the platform. The frequencies of jumping were chosen to represent what is considered to be the most achievable frequency range for rhythmic jumping activity [2,5]. The harmonic, vertical-direction vibrations of the platform having a magnitude, $a_p = 2\ m/s^2$ were studied only. The vibration frequency (f_p) was set to be the same as the metronome frequency (f_a) in all trials involving the vibration of the platform.

In this experiment, a novel aspect was introduced, involving the timing of jumps relative to the position of the platform in its vibration cycle. Fig. 2 illustrates the timing of jumps for two cases. In the first case (Fig. 2a), the mid-flight phase of the jump cycle coincides with the highest position in the vibration cycle, while the mid-contact phase aligns with the lowest position. The second case (Fig. 2b) is the opposite of the first.

Four specific timings were utilised in the tests, which involved instructions to the TSs to land at instances that coincided with the following positions of the platform in each vibration cycle:

(i) The reference position and on the way down (mid-down), corresponding to the case in Fig. 2a,
(ii) The lowest position (trough),
(iii) The reference position and on the way up (mid-up), corresponding to the case in Fig. 2b, and
(iv) The highest position (peak).

These timings are illustrated in Fig. 3 by showing the intended instance of landing (indicated by the beat) relative to the platform displacement profiles.

Platform frequency and magnitude were specified by inputting drive files to the VSimulators. The metronome beats were generated as audio signals and fed into the VSimulators along with the drive files targeting the desired frequency and timing. Thus, each TS jumped at three target frequencies on the non-vibrating platform, and at four target timings at each of the three target frequencies on the vibrating platform, resulting in a total of 15 test configurations per TS (Table 2). These configurations utilised in this study are part of a larger experimental campaign that

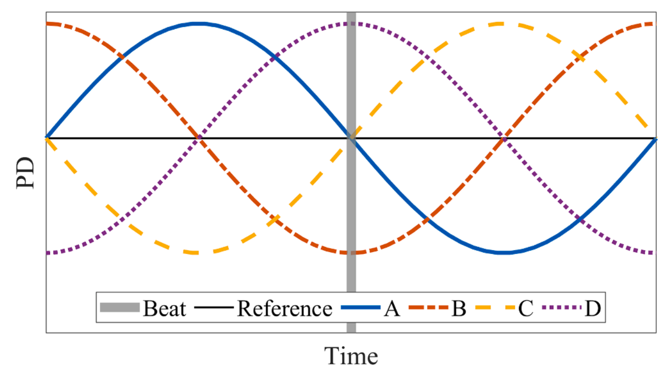

Fig. 3. Metronome beat timing relative to platform displacement (PD): mid-down (A), trough (B), mid-up (C), and peak (D); Platform's reference position is indicated by a horizontal line.

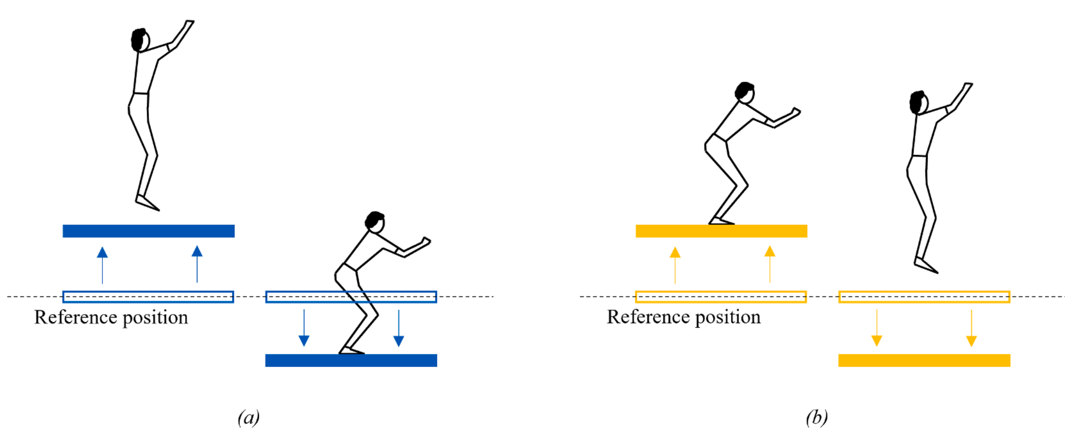

Fig. 2. Illustration of the timing of the jumping action relative to the surface vibration: (a) Mid-flight phase at the highest and mid-contact phase at the lowest positions in the vibration cycle (b) Mid-contact phase at the highest and mid-flight phase at the lowest positions in the vibration cycle.

Table 2
Test configurations.

Configuration #	Jump frequency, f_a [Hz]	Vibration frequency, f_p [Hz]	Vibration level, a_p [m/s^2]	Metronome beat timing	Configuration ID
1	2.0	0.0	0	–	NV2.0X
2		2.0	2	Mid-down	V2.0A
3			2	Trough	V2.0B
4			2	Mid-up	V2.0C
5			2	Peak	V2.0D
6	2.4	0.0	0	–	NV2.4X
7		2.4	2	Mid-down	V2.4A
8			2	Trough	V2.4B
9			2	Mid-up	V2.4C
10			2	Peak	V2.4D
11	2.8	0.0	0	–	NV2.8X
12		2.8	2	Mid-down	V2.8A
13			2	Trough	V2.8B
14			2	Mid-up	V2.8C
15			2	Peak	V2.8D

involved 39 test configurations per TS. The rest 24 configurations, not studied here, had a frequency of jumping different from the respective vibration frequency.

An ID is introduced for each configuration in Table 2 for easy reference. The ID starts with NV/V for tests on non-vibrating/vibrating platform conditions, followed by the target frequency of jumping (2.0, 2.4 or 2.8) and the information about the target timing of jump (X for the non-vibrating platform, and A, B, C or D for four timings on the vibrating platform). Each TS performed three nominally identical trials of jumping for each of the 15 test configurations, which are identified by the trial number at the end of the ID. For example, the second trial of jumping at 2.0 Hz on the non-vibrating platform is referred to as NV2.0X2.

2.3. Test procedure

The duration of a trial was determined so to ensure the recording of 40 cycles of jumping. The data acquisition lasted 20 s for jumping at 2.0 Hz, 17 s for jumping at 2.4 Hz, and 15 s for jumping at 2.8 Hz. These durations of the trails were chosen to both not exhaust the TSs by unnecessarily prolonging their jumping and to have enough jumping cycles to capture inherent variations in GRF [2]. The test design was counterbalanced by employing randomisation of test configurations, which refers to the order in which the TSs were exposed to the test configurations [16]. This approach was used to minimise the potential effects of motor learning. Additionally, the order of test configurations for the three trials varied independently from one another, as they were randomised separately. There were 20 s resting intervals between consecutive trials. In addition, after completing every 13 trials, the TSs were provided with a minimum rest period of ten minutes, allowing them to rest for as long as necessary to minimise fatigue. During the rest period after each trial, the TSs were asked to report their subjective rating of vibration on a rating scale from 0 to 10 (0 for vibration not perceived and 10 for unacceptable vibration).

2.4. Data pre-processing

The vertical GRF and the vertical displacements of the left toe marker and floor marker were analysed in this study. They were low-pass filtered using a fourth-order zero-phase Butterworth filter with a cut-off frequency of 10 Hz. In preparation for the analysis, the GRF signal was normalised by the TS's weight. The measured force signal included the inertia of the force plate on which the TS performed jumping. This inertia force was subtracted from the signal before the analysis. The relative displacement of the toe concerning the floor in the vertical direction was calculated. Furthermore, the corresponding minimum height of the toe marker was subtracted from the relative displacement in each trial to remove the height of the sole of the TS's shoes from the data. Similarly, the height of the platform marker was subtracted from the platform displacement data. The final 25 cycles of the data recorded in each trial were selected for analysis.

3. Parameter extraction

Both objective and subjective measures of human response to vibration were observed to investigate the impact of vertical vibrations on rhythmic jumping. The achieved frequency of jumping, the impact ratio (i.e., the peak GRF normalised by TS's weight, W), the contact ratio (i.e.,

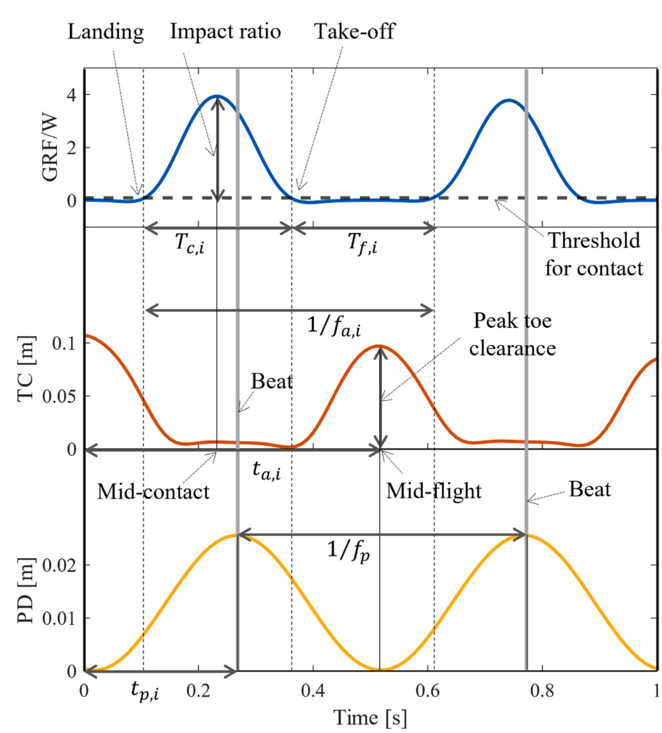

Fig. 4. Extracting objective variables on a c–b–c basis from time-histories of GRF normalised with the jumper's weight (GRF/W), toe clearance (TC), and platform displacement (PD).

the contact duration to the period of jumping ratio), the peak toe clearance (i.e., the peak relative distance between the vertical displacement of the toe and the platform), and the timing of the jump relative to the platform's motion were evaluated on a cycle-by-cycle (c–b–c) basis. They represent the objective measures. The TS's rating of vibration recorded on completion of a trial is taken as a representation of the subjective measure. Both objective and subjective measures of the human response are expected to vary between nominally identical trials of rhythmic jumping performed by different people as well as by the same person. In addition, objective measures are also expected to vary on a c–b–c basis within the same trial.

3.1. Frequency of jumping, impact ratio, peak toe clearance, contact ratio

The frequency of jumping, impact ratio, peak toe clearance and contact ratio were extracted on a c–b–c basis and are illustrated in Fig. 4, where two cycles are shown for TS04 jumping to the metronome beat at 2.0 Hz and targeting to land at the peak position of the platform (V2.0D2). The suffix i is introduced to denote the c–b–c values of the variables, as they vary slightly between cycles due to the human inability to keep perfect timing. In this particular trial, the TS landed approximately a quarter cycle of jumping earlier than instructed, which means that they were approximately in the middle of their contact phase at the time of the metronome beat. The correlation (or lack of it) between the actual and target timing is one of the more interesting factors that have the potential to shed light on human preferences in timing their contact and flight relative to the moving floor.

To separate the flight and contact phases in the GRF data, a threshold of 10% of the weight (0.1 W) of the corresponding TS was adopted. The time interval during which the force is greater than the threshold is considered to represent the contact phase, while the time interval below the threshold is assumed to represent the flight phase. The contact phase of a cycle of jumping starts with landing and ends with take-off whereas the flight phase is between take-off and the landing of the next cycle (Fig. 4). The c–b–c period of the cycle of jumping ($1/f_{a,i}$, where $f_{a,i}$ is the c–b–c frequency of jumping) can be expressed as the sum of c–b–c durations of contact ($T_{c,i}$) and flight ($T_{f,i}$) phases (i.e., $1/f_{a,i} = T_{c,i}+T_{f,i}$) as shown in Fig. 4.

3.2. Timing of jumps

The timing of the jumper's motion relative to the platform's motion is expressed in the form of the discrete relative phase (DRP) [17]:

$$DRP_i = (t_{a,i} - t_{p,i}) \times f_a \times 360^{\circ} \quad (1)$$

Table 3
Summary of events corresponding to numerical values of DRP.

Target timing	DRP [°]	Platform position corresponding to specific gait events			
		Landing	Mid-contact (Peak GRF)	Take-off	Mid-flight (Peak TC)
A	0	Mid-down	Trough	Mid-up	Peak
B	90	Trough	Mid-up	Peak	Mid-down
C	180	Mid-up	Peak	Mid-down	Trough
D	270	Peak	Mid-down	Trough	Mid-up

where $t_{a,i}$ is the time to peak toe clearance at the i^{th} cycle and $t_{p,i}$ is the time to peak platform displacement at the i^{th} cycle (Fig. 4). Note that the target frequency of jumping, f_a is nominally the same as the platform's vibration frequency, f_p.

DRP ranges between 0° and 360°, as shown in Fig. 5. A DRP of 0° indicates that the peak toe clearance and peak platform displacement occur at the same time instant. In addition, it also indicates that the mid-contact phase of the jumping action occurs at the trough position of the platform and therefore the landing occurs at the mid-down instant while the take-off occurs at the mid-up position of the platform. Note that this interpretation holds only under the assumption that the contact ratio is equal to 0.5. In other cases, it is an approximate interpretation of the timing of the physical events. A summary of the events corresponding to numerical values of DRP, if the instructed landing timings are executed to perfection is given in Table 3 for easy reference. The metronome timings A, B, C, and D (Fig. 3) will result in DRP values of 0, 90, 180 and 270° (Table 3), respectively, if executed as expected.

Note that an increase in DRP indicates a delay in the timing. For example, if a DRP of 90° is obtained when 0° was expected, it means that the jump was delayed by a quarter cycle. Landing while the platform is

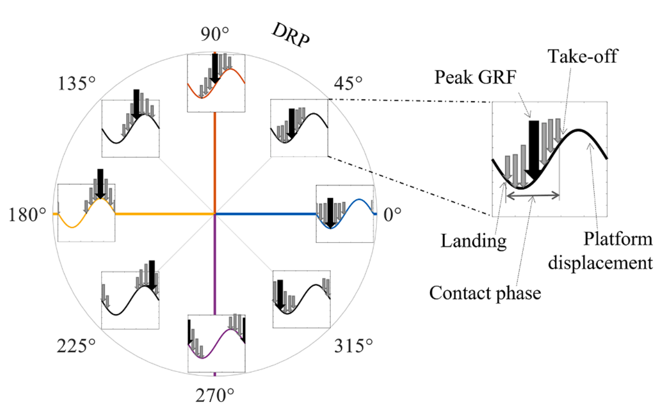

Fig. 5. Illustration of DRP as the jumper's timing relative to the platform's vibration cycle during rhythmic jumping.

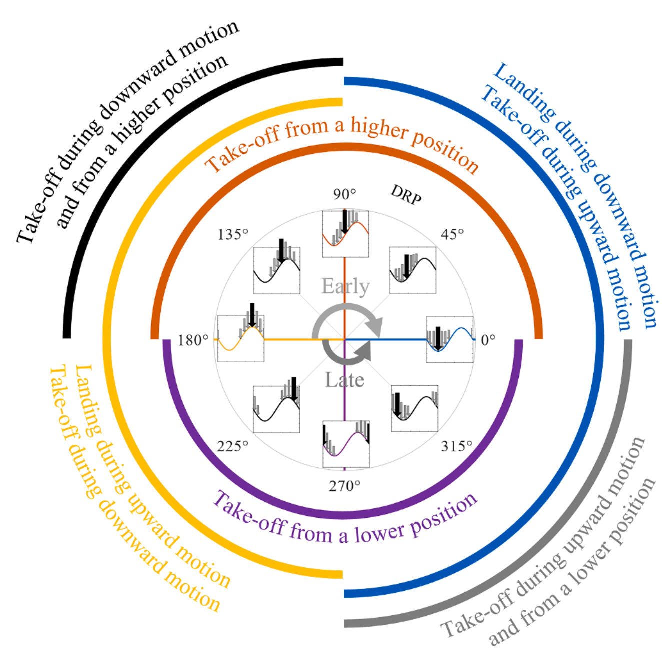

Fig. 6. Spatiotemporal interpretation of DRP.

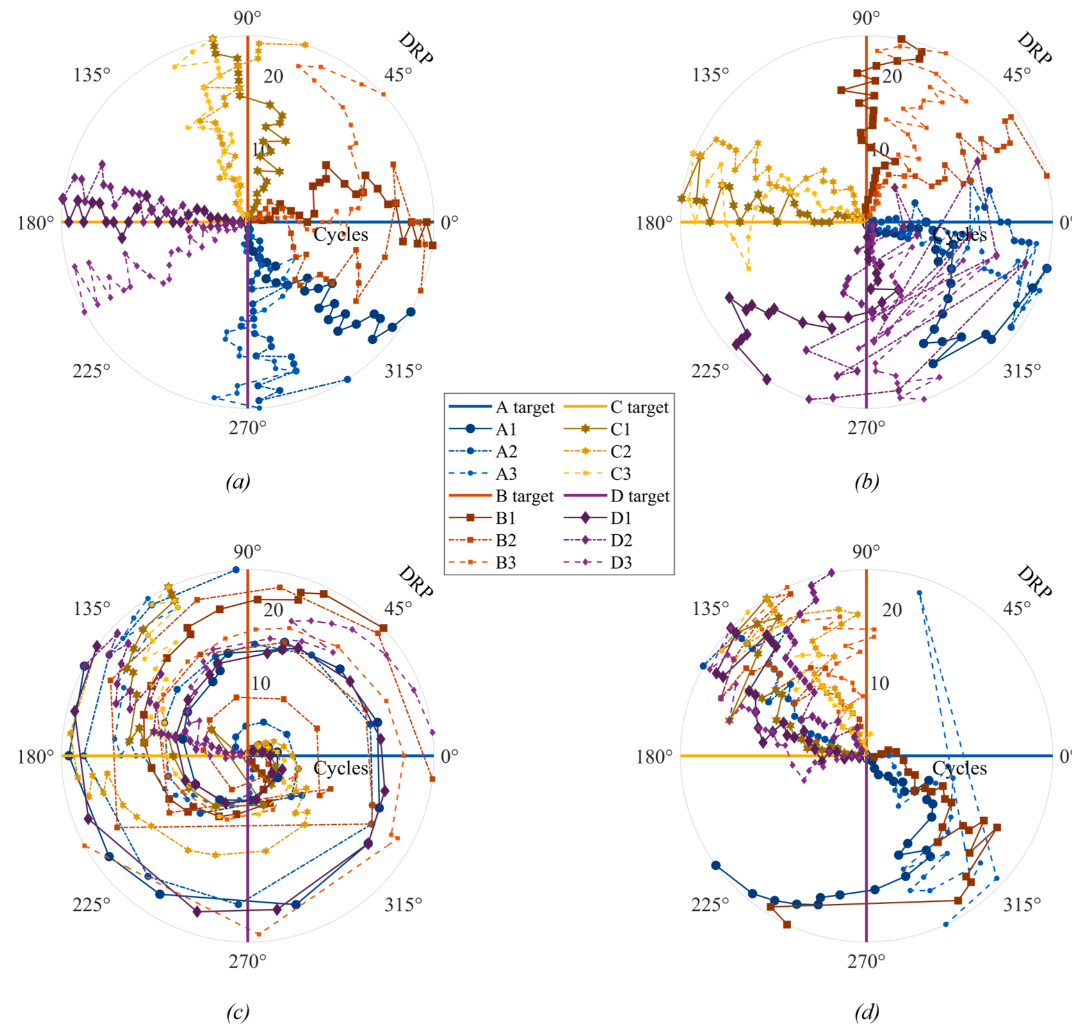

Fig. 7. Polar plots of target and c–b–c DRP for three trials of jumping at 2.0 Hz target (V2.0) and four target timings (A-D) by (a) TS04 (b) TS05 (c) TS07, and (d) TS09.

moving upwards will yield a DRP between 90° and 270°. This corresponds to taking off while the platform is moving downwards. A DRP between 0° and 180° enables taking off from a higher position in the platform's vibration cycle compared to DRP between 180° and 0°. Furthermore, a DRP between 90° and 180° corresponds to landing during the platform's upward motion and therefore a take-off from a higher platform elevation. Conversely, a DRP between 270° and 0° will correspond to landing during the platform's downward motion and take-off from a lower position of the platform. This spatiotemporal interpretation of DRP is visualised in Fig. 6.

The variation of DRP between three trials and across cycles of the same trial is illustrated through polar plots in Fig. 7 for four TSs jumping at 2.0 Hz and all four target timings (V2.0A-D). In Fig. 7a, TS04 timed their mid-contact event (rather than the landing event) to coincide with the beat, thus landing a quarter of a cycle earlier than expected. This TS maintained consistency in the achieved timing across the trials. Fig. 7b shows the trials by TS05, where the landings are close to the targets, with noticeable inconsistency in timing. A case wherein the TS neither met the target nor maintained consistent timing is illustrated in Fig. 7c. TS07 constantly slipped out of the target timing in all the trials, except in the second trial targeting landing at peak (D2). TS09 shifted to a preferred DRP between 90° and 180° except for three trials (A1, A3, and B1) as shown in Fig. 7d. These examples provide insight into large variations in TSs' execution of the same instruction, which is especially relevant in studying crowd actions.

4. Results and discussion

The effect of vibrations on jumping was quantified by analysing the frequency, timing, impact ratio, peak toe clearance, contact ratio and the subjective rating of vibration. The achieved frequency and timing were observed to establish whether the TSs had a preference while jumping at the three target frequencies. Moreover, the peak toe clearance, impact ratio and contact ratio were analysed to investigate their variation with achieved jump timing and frequency, and the correlations between each other. Finally, the potential correlation between objective and subjective responses was examined.

4.1. Frequency of jumping

Although rhythmic jumping activity can be performed between 1 and 4 Hz, the most achievable range of frequencies is 2–3 Hz [2,3,5,18]. A previous study [1] concerning jumping on non-vibrating surfaces found that the jumpers achieved the target of 1 Hz the best in terms of the average value of a trial, whilst the c–b–c variation was the least for the target of 2 Hz amongst the three frequencies of 1, 2 and 3 Hz. This

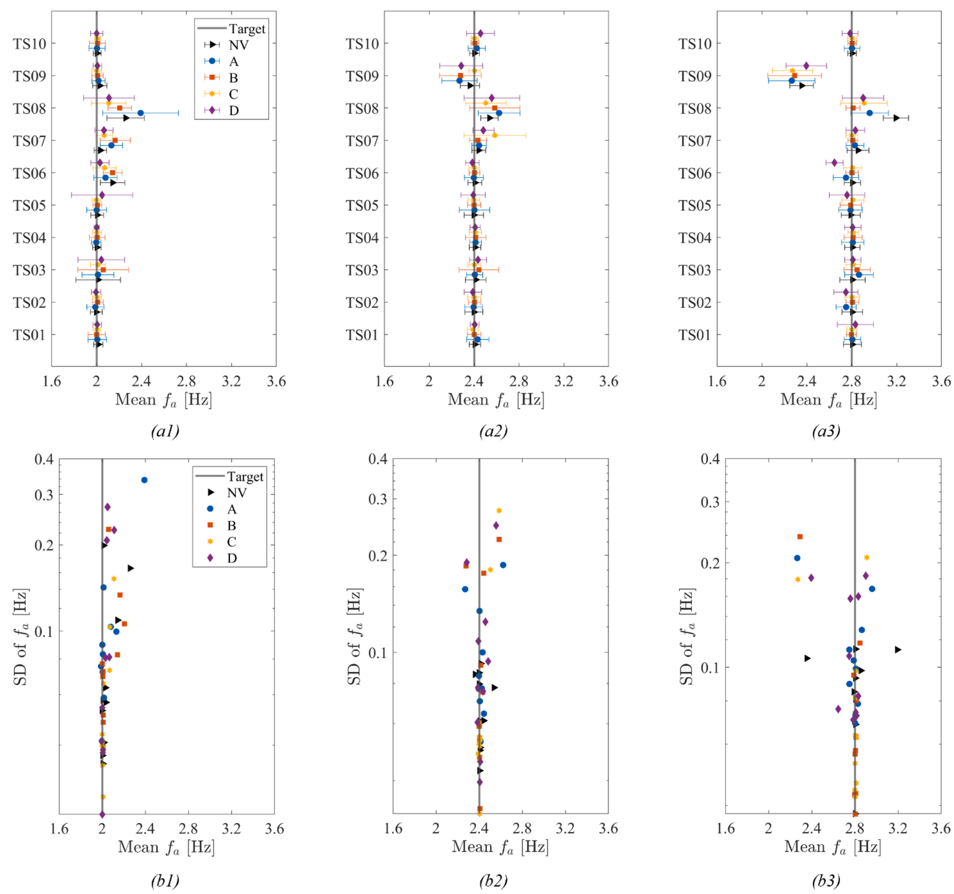

Fig. 8. Mean ± SD (b) SD versus mean of frequency of jumping across the cycles and three trials by ten TSs at target frequencies 2.0 Hz (a1, b1), 2.4 Hz (a2, b2), and 2.8 Hz (a3, b3) on the non-vibrating (NV) platform, and four target timings (A-D) on the vibrating platform; y-axes of (b) are on a logarithmic scale of base 10.

shows that faster jumping is difficult to achieve in comparison with slower.

The current study consists of two steps to investigate the frequency of jumping:

(i) an initial exploratory data analysis (EDA) aimed at gaining insights, identifying patterns, detecting outliers, and selecting appropriate techniques for further analysis, and
(ii) an inferential statistical analysis (ISA) to draw conclusions using appropriate techniques.

Repeated Measures Analysis of Variance (RM ANOVA) was employed to analyse measurements taken over multiple time points and conditions. This two-step process allows for a comprehensive examination of the data and facilitates drawing meaningful conclusions based on statistical evidence.

4.1.1. Exploratory data analysis (EDA)

The mean frequency of jumping was compared with the respective target for each test configuration and TS in Fig. 8a1 – a3. The standard deviation (SD), which is a measure of inconsistency in timing, was plotted against the mean in Fig. 8b1 – b3.

While jumping on the non-vibrating platform, the TSs generally achieved mean frequencies close to their targets, except for TS06 and TS08 aiming at 2.0 Hz, TS08 at 2.4 Hz, and TS08 and TS09 at 2.8 Hz, whose mean frequencies deviated slightly from their targets. On the vibrating platform, TS06, TS07, and TS08 had mean frequencies slightly away from the target of 2.0 Hz, TS07, TS08, and TS09 from the target of 2.4 Hz, and TS06, TS08, and TS09 from the target of 2.8 Hz. Notably, TS09 consistently had a mean frequency between 2.0 and 2.4 Hz, while TS08′s frequency was consistently higher than the target. These examples highlight TS-specific behaviours that compromise accuracy regardless of the frequency of jumping and platform configurations. White et al. [12] also observed a similar scenario in their tests where one of the seven TSs did not adhere to the metronome, resulting in a consistent mean frequency of 1.55 Hz for target frequencies between 1.5 and 3 Hz. In the population of TSs studied here, at least 20% of them exhibited mean frequencies slightly, but notably away from their respective targets.

When the target frequency was 2.0 Hz, the maximum SD of the frequency was 0.20 Hz on the non-vibrating platform and 0.34 Hz on the vibrating platform. For the 2.4 Hz target, the maximum SD was 0.09 Hz on the non-vibrating platform and 0.30 Hz on the vibrating platform. Similarly, for the 2.8 Hz target, the maximum SD was 0.11 Hz on the non-vibrating platform and 0.24 Hz on the vibrating platform. Overall, the maximum SD on the vibrating platform was higher, compared to that on the non-vibrating platform, for all three frequencies, indicating a wider spread in the frequencies of individual TSs. On the non-vibrating platform, the highest SD was observed for the 2.0 Hz target, followed by 2.8 Hz, and the lowest for the 2.4 Hz target. On the vibrating platform, the maximum SD decreased with an increase in frequency. Furthermore, for the highest frequency of 2.8 Hz, the SD was lower when the target timings were B and C compared to A and D, with only a few exceptions. This trend diminished as the target frequency decreased.

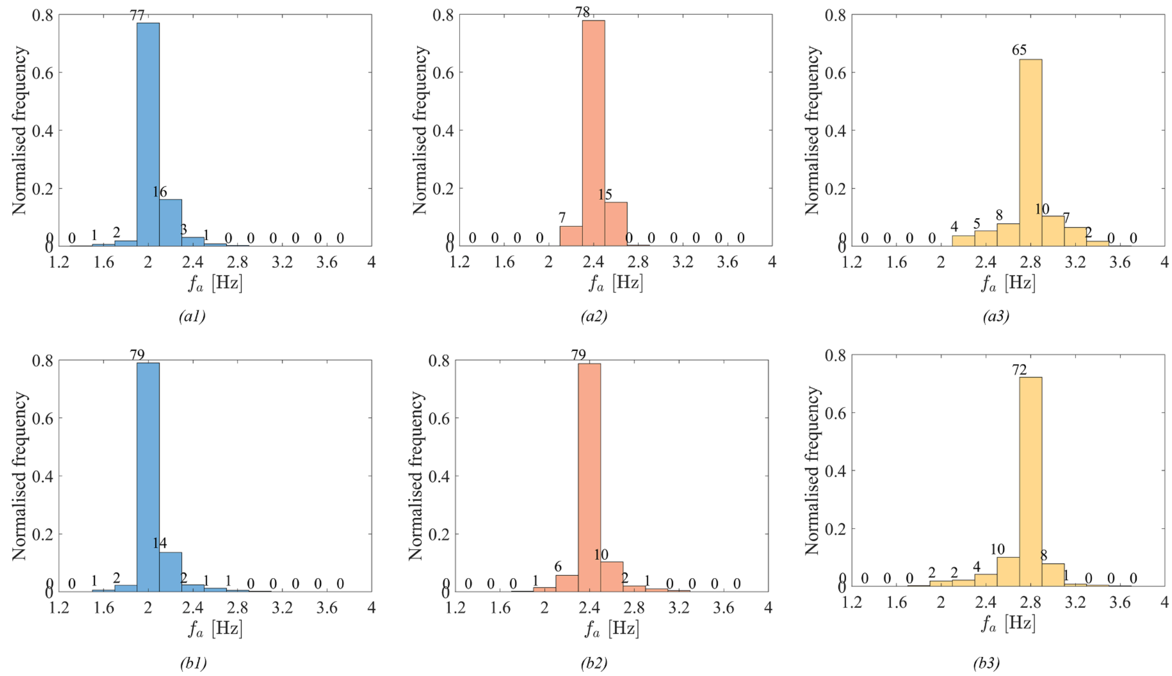

Fig. 9. Histograms of c–b–c frequency of jumping by all TSs on the (a) non-vibrating, and (b) vibrating platform at targets 2.0 Hz (a1, b1), 2.4 Hz (a2, b2), and 2.8 Hz (a3, b3).

4.1.2. Inferential statistical analysis (ISA)

Based on the initial EDA, four aspects of target frequency achievement were investigated through ISA:

(i) whether the TSs achieved the target frequencies,
(ii) the dependency of the first aspect on the target frequency,
(iii) the preferred frequency of jumping (slower or faster than the target) when the target was not achieved, and
(iv) the dependency of the third aspect on the target frequency.

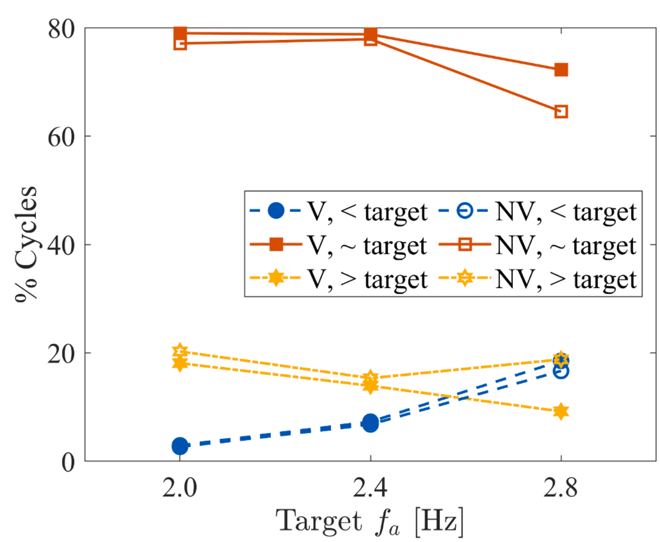

Fig. 10. Percentage cycles with c–b–c frequency of jumping at, less than, and greater than the target on the vibrating (V) platform in comparison with that on the non-vibrating (NV) platform.

The study included a sample size of 30, with 10 TSs performing 3 trials of jumping on the non-vibrating platform at each target frequency. For tests conducted on the vibrating platform, the sample size was 120, with 10 TSs, 4 target timings, and 3 trials for each of the target frequencies. The histograms of the c–b–c frequency of jumping from all trials performed by all TSs were plotted separately for the three target frequencies with a bin width of 0.2 Hz. These are presented in Fig. 9a and b, respectively, for the non-vibrating and vibrating conditions of the platform.

The cycles of jumping from all trials performed by all TSs were divided into three groups: at target (i.e., within ±0.1 Hz of the target frequency), less than target (i.e., less than target −0.1 Hz) and greater than target (i.e., greater than target +0.1 Hz), for each frequency and both conditions of the platform. This is visualised in Fig. 10.

The RM ANOVA test was conducted using SPSS, a commonly used statistical software suite for statistical analysis. To account for multiple comparisons, pairwise comparisons were performed with Bonferroni adjustment. The statistical test assumed that observed effects were considered significant at the 0.05 level ($p = 0.05$), which corresponds to a confidence level of 95%. To assess the adequacy of the sample size, power calculations were performed for each test. A test with a power value (P) below 0.8 is generally considered underpowered, indicating insufficient statistical power to detect meaningful effects. Insufficient statistical power can compromise the ability to detect meaningful effects and draw definitive conclusions.

For this study, a two-way RM ANOVA test was conducted with two factors: platform condition (NV and V) and target frequency of jumping (2.0, 2.4, and 2.8 Hz). The dependent variables analysed were the percentage of cycles at the target frequency, the percentage of cycles below the target frequency, and the percentage of cycles above the target frequency.

4.1.2.1. Target frequency achievement. The TSs achieved target frequencies (i.e., within ±0.1 Hz of their target) in 65–78% of the cycles on the non-vibrating platform and 72–79% on the vibrating platform by following the metronome beat set at all three frequencies of jumping. The results indicate that the percentage of cycles near the target was significantly greater compared to those below and above at all three frequencies, under both non-vibrating and vibrating conditions of the platform ($p < 0.01$ for pairwise comparisons). This suggests that the TSs demonstrated a high level of frequency precision throughout the trials when prompted by an audio metronome. It is important to note that the power for all these tests was 1.00, indicating ample statistical power to detect meaningful effects.

4.1.2.2. Frequency-dependence of target frequency achievement. On the non-vibrating platform, the TSs achieved a frequency of jumping within ±0.1 Hz of the target in over 77% of the cycles when aiming for NV2.0 and NV2.4 configurations, compared to 65% when aiming for NV2.8 configuration (Fig. 10). This suggests a difficulty among the TSs to jump at 2.8 Hz compared to 2.0 and 2.4 Hz on the non-vibrating platform, which aligns with previous literature [1]. However, the significance levels of these effects were only 0.28 and 0.22, respectively. Nevertheless, the statistical power for this test was only 0.42 implying the inadequacy of the sample size used for this case. Hence, the significance of these effects could not be firmly established based on the significance level, but they cannot be confidently dismissed based on power alone. Therefore, future research with a larger sample size should provide more robust evidence for this effect.

Furthermore, on the vibrating platform, there was no significant difference in the percentage cycles at the target between the frequencies. However, this effect could not be confirmed due to the lack of sufficient statistical power ($P = 0.43$). The difference in target achievement between non-vibrating and vibrating platforms was also not confirmed due to a lack of adequate statistical power ($P = 0.06$, 0.05 and 0.26 at frequencies 2.0, 2.4 and 2.8 Hz, respectively).

4.1.2.3. Frequency preference when target frequency not achieved. The percentage of cycles with a c-b-c frequency less/greater than the target, visualised from the symmetry of histograms about the target frequency bin in Fig. 9, indicates the TS's tendency to jump faster or slower than the specified target. When the TSs were away from the target, they showed a preference to jump slightly faster in both NV2.0 ($p = 0.01$) and V2.0 ($p < 0.01$) configurations. This finding aligns with previous studies on jumping under non-vibrating conditions [2,18], which have reported that jumping below 2.0 Hz is challenging. However, there was no significant preference observed for jumping slower or faster when away from the target for NV2.4 ($p = 0.47$) and V2.4 ($p = 0.08$) configurations. Therefore, the spread around the target depicted in Fig. 9 can be attributed to inherent inter- and intra-subject variability rather than a preference to jump slower or faster. Furthermore, a significant preference was observed for jumping slightly slower when away from the target for the V2.8 configuration ($p < 0.01$), but not for the NV2.8 configuration ($p = 1.00$). The power for these tests was 1.00, meaning sufficient statistical power to detect substantial effects.

4.1.2.4. Frequency-dependent preference when target frequency not achieved. On the non-vibrating platform, a significant difference in the percentage of cycles with a c–b–c frequency lower than the target was observed between NV2.8 and NV2.0 ($p = 0.02$), but no significant difference was found between NV2.8 and NV2.4 ($p = 0.18$). Additionally, there was no significant difference between NV2.0 and NV2.4 ($p = 1.00$). However, the observed power for these tests was only 0.69, suggesting insufficient statistical power to detect significant effects. On the vibrating platform, the difference in the percentage of cycles with a c–b–c frequency lower than the target for the V2.8 configuration was found to be significantly different from that for V2.0 ($p < 0.01$) and V2.4 ($p < 0.01$) configurations. However, there was no significant difference between V2.0 and V2.4 configurations ($p = 0.29$). The statistical power for these tests was 1.00, indicating sufficient statistical power to detect significant effects. Between the non-vibrating and vibrating platforms, the difference in percentage cycles with a c–b–c frequency less than the target was not significant at 2.0 Hz ($p = 0.95$), 2.4 Hz ($p = 0.90$), and 2.8 Hz ($p = 0.65$). However, these were underpowered with observed power of 0.05, 0.05 and 0.07, respectively.

Furthermore, the only significant difference observed in the percentage of cycles with a c–b–c frequency greater than the target was between the V2.0 and V2.8 configurations. However, due to a lack of sufficient statistical power ($P = 0.75$), it was not possible to confirm this difference. The difference in percentage cycles with a c–b–c frequency greater than the target was not significant between NV and V configurations at 2.0 Hz ($p = 0.65$) and 2.4 Hz ($p = 0.77$), whereas the difference was significant at 2.8 Hz ($p = 0.05$). These tests were also underpowered with observed power of 0.07, 0.06 and 0.52, respectively.

4.1.3. Discussion

Based on EDA, the spread in the frequencies of individual TSs, as represented by the SD calculated for each test configuration, was higher on the vibrating platform compared to the non-vibrating platform. The lowest spread was at 2.4 Hz on the non-vibrating platform (NV2.4) and 2.8 Hz on the vibrating platform (V2.8). Among the V2.8 configurations, the SD was the lowest for target timings of B and C. This finding warrants further investigation based on achieved timings.

In terms of ISA, there is an indication that consistent jumping at the highest frequency of 2.8 Hz was more challenging on the non-vibrating surface compared to the vibrating surface, although tests did not have sufficient statistical power to confirm this. This comparison between NV2.8 and V2.8 configurations suggests the potential for better synchronisation of crowds with faster audio stimuli on the vibrating surface. Future research should examine whether this tendency extends to frequencies above 2.8 Hz. Additionally, when the target frequency was not achieved, TSs tended to prefer jumping slightly faster for NV2.0 and V2.0 configurations, and slightly slower for V2.8 configurations. There was no significant preference observed for NV2.4, V2.4, and NV2.8 configurations.

The results demonstrate that 2.4 Hz is the most achievable frequency for rhythmic jumping on both non-vibrating and vibrating surfaces. A frequency of 2.0 Hz, on the other hand, lies at the lower end of the most achievable frequency range for both platform conditions, resulting in a tendency to jump slightly faster. Conversely, 2.8 Hz represents the higher end of the most achievable range. It poses challenges in reaching the target frequency on the non-vibrating platform, while also eliciting a tendency to jump slightly slower on the vibrating platform.

4.2. Timing of jumps

The analysis approach to investigate the achievement of target timing at three target frequencies of jumping on the vibrating platform includes an initial EDA followed by an ISA, as previously described (Section 4.1).

4.2.1. Exploratory data analysis (EDA)

The mean and SD of DRP over cycles and three trials of each test configuration on the vibrating platform are plotted in Fig. 11. When aiming for a frequency of 2.0 Hz (Fig. 11a1 and b1), the mean values of the DRP achieved were inconsistent. Specifically, the values varied between being near the target and early. The SD of DRP ranged between 10 and 80°, indicating a wide spread of data. In the cases targeting 2.4 Hz (Fig. 11a2 and b2), the mean DRP values were mostly close to the target, with SD ranging from 10 to 70°. At the target frequency of 2.8 Hz (Fig. 11a3 and b3), there was a noticeable shift in mean DRP values towards 135°, indicating a preference in timing. Moreover, the SD ranged from 5 to 50° when the DRP was near 135°, compared to 20 to

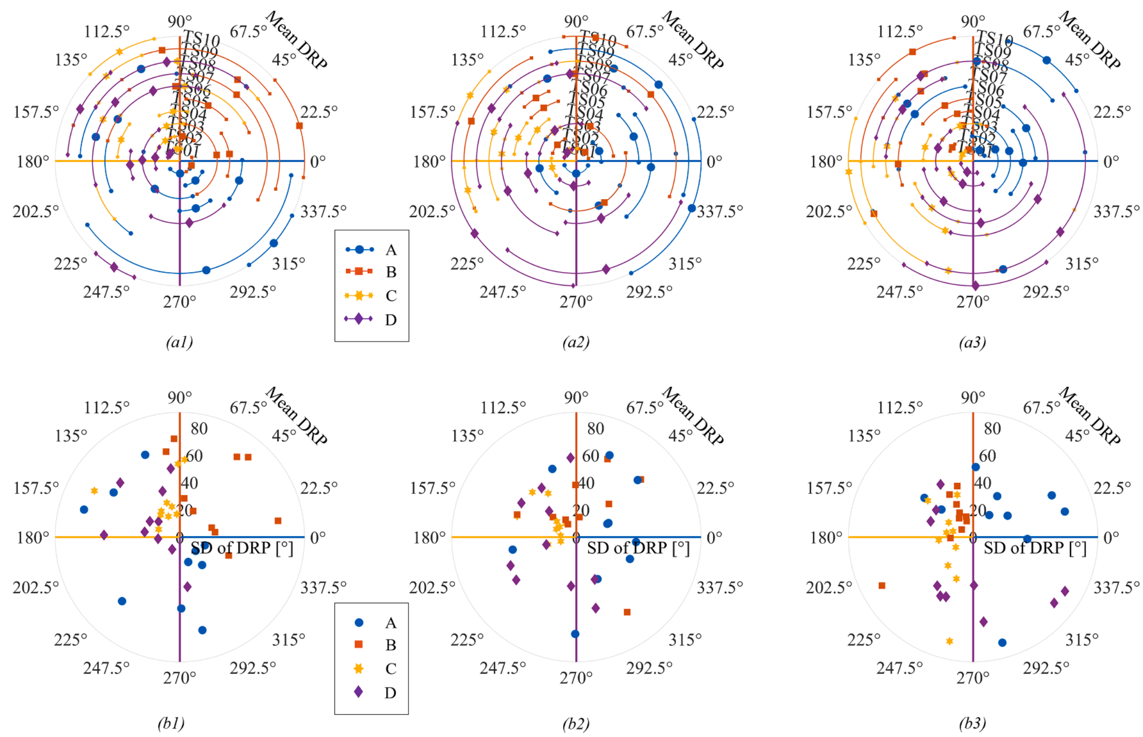

Fig. 11. Polar plots showing (a) circular mean ± circular SD (b) circular SD versus circular mean of DRP across the cycles and three trials by ten TSs on the vibrating platform at four target timings (A-D) and target frequencies 2.0 Hz (a1, b1), 2.4 Hz (a2, b2), and 2.8 Hz (a3, b3).

80° when it deviated from 135°. This suggests a decrease in the spread of DRP when jumping at the preferred timing. However, this shift towards 135° was observed at lower frequencies for only a limited number of trials and cycles. Additionally, there was a reduction in the range of SD (10-60°) when the DRP was near 135° at the 2.4 Hz target, whereas this pattern was not visible at the 2.0 Hz target.

4.2.2. Inferential statistical analysis (ISA)

Based on the observations from EDA, two aspects of target timing achievement were investigated through ISA:

(i) whether the TSs exhibited a preference for timing, and

(ii) the relationship between the timing preference and the target frequency.

This study involved a sample size of 120, with 10 TSs performing 3 trials of jumping at 4 target timings on the vibrating platform for each of the target frequencies. Polar histograms of the c–b–c DRP from all trials of jumping performed by all TSs are shown in Fig. 12 for the three target frequencies. The data were divided between eight bins, each 45° wide, with boundaries set at 22.5°, 67.5°, 112.5°, 157.5°, 202.5°, 247.5°, 292.5° and 337.5°.

If the TSs executed jumping at perfect timing in all the tests, each of these 4 bins: 337.5–22.5°, 67.5–112.5°, 157.5–202.5°, and 247.5–292.5° would have 25% of the data points. Allowing for slight

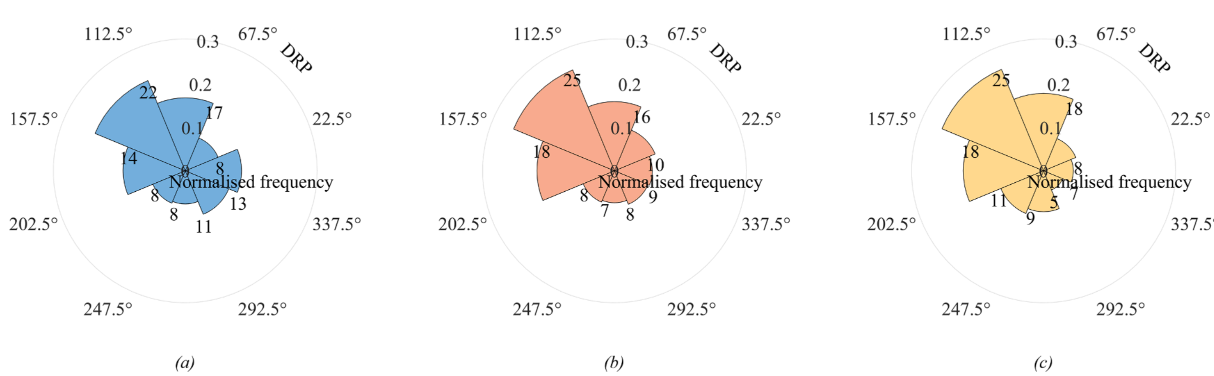

Fig. 12. Polar histograms of c–b–c DRP for all TSs and all target timings at target frequencies (a) 2.0 Hz, (b) 2.4 Hz, and (c) 2.8 Hz on the vibrating platform.

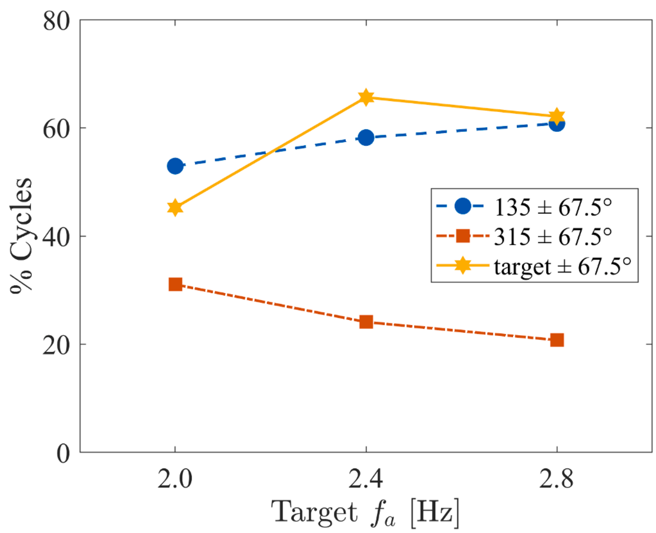

Fig. 13. Percentage cycles with c–b–c DRP around the target, 135°, and 315°.

variations in the timing, these four bins are still expected to dominate whilst some (a small amount) of the data would move to the neighbouring bins. Instead, what happened for all jump frequencies is that 22–25% of the data points were found to belong to 135±22.5° (112.5 – 157.5°) bin and 53–61% to 135±67.5° (67.5° – 202.5°). The percentage cycles with DRP within target ±22.5° ranged between 14 and 28, whereas the percentage cycles within target ±67.5° ranged between 45 and 66. Only 20–32% of the cycles had a DRP in the vicinity of 315° (i.e., 315±67.5° or 247.5.5°–22.5°). This suggests that, in general, there was a preference for a DRP in the vicinity of 135°, irrespective of the frequency of jumping. These are visualised in Fig. 13. As a reminder, a DRP of 135° corresponds to landing during the platform's upward motion and therefore a take-off during downward motion and from a higher elevation of the platform while a DRP of 315° corresponds to landing during the platform's downward motion and take-off during upward motion and from a lower position of the platform (Fig. 6).

A one-way RM ANOVA test was conducted with a single factor, the target frequency of jumping. The three dependent variables analysed were the percentage of cycles with a DRP close to the target, the percentage of cycles with a DRP close to 135°, and the percentage of cycles with a DRP close to 315°.

4.2.2.1. Timing preference. The percentage of cycles with DRP within the range of 135±67.5° is significantly greater than the percentage within the range of 315±67.5° at all three frequencies ($p < 0.01$), indicating a preference towards a DRP ~135° and an aversion towards a DRP ~315°. There is no significant difference between the percentage of cycles close to the target and those with a DRP ~135°. The significance levels were 0.36 for 2.0 Hz, 0.39 for 2.4 Hz, and 1.00 for 2.8 Hz. However, this seemingly equal preference for a DRP ~135° and the respective target timing can be attributed to the overlap between these preference cases for B (target DRP = 90°) and C (target DRP = 180°) configurations. For these configurations, the targets overlap with the range of 135±67.5°. However, the alternate argument that the preference towards 135° is due to this overlap does not hold due to the significant difference between the percentage of cycles with DRP close to 135° and 315°. The statistical power was 0.91 for V2.0 configurations and 1.00 for both V2.4 and V2.8 configurations, indicating sufficient power to detect meaningful effects.

4.2.2.2. Frequency-dependent timing preference. As the target frequency of jumping increases, there is an increase in the percentage of cycles with DRP falling within the range of 135±67.5° and a decrease in the percentage within the range of 315±67.5° (Fig. 13). The significance levels for the comparisons between V2.0 and V2.8 configurations are 0.38 and 0.05, respectively. This suggests that the frequency-dependence on the preference for a DRP ~135° is not statistically significant, while the aversion towards a DRP ~315° is statistically significant. However, it is important to note that these trends could not be firmly established based on the data used in this study due to the limited statistical power of 0.27 and 0.59, respectively, for these two cases.

Furthermore, the achievement of target timing is highest at 2.4 Hz, followed by 2.8 and 2.0 Hz (Fig. 13). The achievement of target timing for V2.0 configurations is significantly different from both V2.4 ($p < 0.01$) and V2.8 ($p < 0.01$) configurations. However, there was no significant difference between V2.4 and V2.8 configurations ($p = 1.00$). The observed statistical power was 0.99 indicating sufficient power to detect meaningful effects.

4.2.3. Discussion

The TSs showed a clear preference for a DRP ~135°, which corresponds to landing during the platform's upward motion and taking off during downward motion and from a higher elevation of the platform. In contrast, a DRP ~315°, which involves landing during the platform's downward motion and taking off during upward motion and from a lower position, was considered the least favourable timing. When the DRP is close to 135°, the platform provides an upward push during most of the contact phase, acting as a springboard for take-off. This timing helps the TSs sustain rhythmic jumping at the specified frequency, unlike the 315° timing. The preference for a DRP ~135° and aversion towards 315° takes precedence over landing precisely on the metronome beat, while still using the beat as a tool for maintaining the target frequency of jumping. It is this preference that helps explain the reduction in SD values of the achieved frequency when the DRP values are close to 135° (Sections 4.1.1 and 4.1.3). Hence, the impact of vibrations on rhythmic jumping, referred to as S2HI, is verified at all three frequencies, with its influence growing as the frequency increases.

White et al. [12] reported an 'antiphase' behaviour between the jumper and the structure at higher frequencies including 2.55 and 3.10 Hz, in contrast to an 'in-phase' behaviour at lower frequencies such as 1.52 Hz observed on a timber beam. Though it was not quantified, this behaviour at higher frequencies supports the preference for a DRP ~135°. However, at lower frequencies, rather than preferring 'in-phase' behaviour as reported by White et al. [12], there was only a diminished inclination towards DRP ~135°. Based on EDA, most jumps occurred either at the target timing or slightly ahead, indicating a different trend. Given the absence of information about the timing of the metronome beat relative to the vibrations, the 'in-phase' behaviour observed by White et al. [12] cannot be conclusively considered a preference; it could potentially be the TSs following the beat. Consequently, their observation at lower frequencies can only be used to illustrate a contrasting behaviour when compared to higher frequencies. In essence, when considering White et al.'s [12] observations and the various frequencies employed in their experiments, the outcomes identified in the present study might conceivably extend to other achievable frequencies and supporting structures involving HSI. However, further tests are needed to substantiate this notion.

Based on the results of the EDA, which showed that the TSs were either on time or early, and the ISA, which indicated the least aversion towards a DRP ~315° at the 2.0 Hz target, it can be concluded that the TSs' performance was largely influenced by the test constraints. It is likely that the TSs became impatient with the slower metronome beat at 2.0 Hz and landed slightly early. In contrast, jumping at the 2.4 Hz target demonstrated the best achievement of the target timing and therefore was primarily controlled by the metronome beat. On the other hand, the highest preference for a DRP ~135° was observed at the 2.8 Hz target,

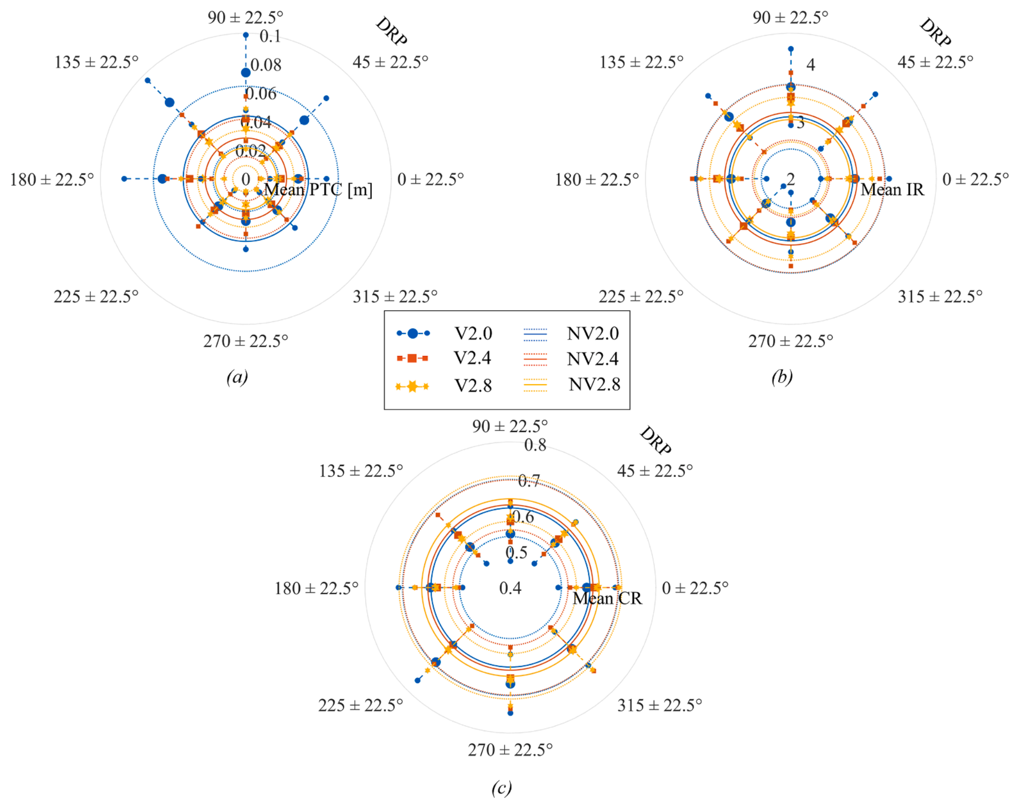

Fig. 14. Polar plots showing mean ± SD of c–b–c (a) peak toe clearance (PTC), (b) impact ratio (IR), and (c) contact ratio (CR) for eight DRP-based bins for jumping on the vibrating (V) platform for target frequencies 2.0, 2.4, and, 2.8 Hz, in comparison with those on the benchmark non-vibrating (NV) platform.

suggesting a response most influenced by the vibrations. Based on these findings, it can be categorised that rhythmic jumping is constraint-driven at low frequencies, audio stimulus-driven at moderate frequencies, and vibration-driven at high frequencies.

4.3. Peak toe clearance, impact ratio, contact ratio

Impact ratio, contact ratio, and toe clearance hold significance in structural design considerations. Therefore, the influence of achieved timing, represented by the DRP, on these parameters was examined. Additionally, the correlations between these parameters were also studied. Furthermore, their numerical values were compared with those reported in the literature.

4.3.1. Effect of timing

The mean and SD of c–b–c peak toe clearance, impact ratio, and contact ratio were calculated for eight bins based on the DRP values achieved when jumping on the vibrating platform. These values were compared with the benchmark values obtained on the non-vibrating platform as shown in the polar plots in Fig. 14.

The mean values of the c–b–c peak toe clearance (Fig. 14a) and impact ratio (Fig. 14b) were higher, while the mean c–b–c contact ratio (Fig. 14c) was lower for jumping on the vibrating platform compared to the non-vibrating platform for bins with DRP closer to 135°. Conversely, for the bins closer to 315°, the mean c–b–c peak toe clearance and mean impact ratio were lower, while the mean c–b–c contact ratio was higher on the vibrating platform compared to the non-vibrating platform. Additionally, the mean c–b–c peak toe clearance decreased with an increase in frequency on both the non-vibrating and vibrating platforms (Fig. 14a). The mean c–b–c contact ratio increased with an increase in frequency on the non-vibrating platform and for most bins on the vibrating platform (Fig. 14c). The mean c–b–c impact ratio was highest at 2.4 Hz, followed by 2.0 and 2.8 Hz on the non-vibrating platform (Fig. 14b), which is consistent with previous research [1] where the mean impact ratio was highest at 2.0 Hz among frequencies of 1.0, 2.0, and 3.0 Hz. However, on the vibrating platform, the mean impact ratio increased with a decrease in frequency for bins with DRP close to 135°, while for bins closer to 315°, it was highest at 2.4 Hz, followed by 2.8 and 2.0 Hz. Furthermore, the SD of all three parameters decreased with an increase in frequency. In summary, the force generated during jumping was the highest at the preferred timing of DRP ~135°.

4.3.2. Correlations

It is well known from the literature that the higher the jump, the greater the impact and the shorter the contact [1,9,19]. A quadratic fit was adopted in a previous study [1] to model the inverse relationship between the impact ratio and the contact ratio for jumping between 1 and 3 Hz on a non-vibrating surface. Another interesting finding [1] concerning jumping between 1 and 3 Hz on the non-vibrating surface is that the impact ratio increases with the frequency of jumping, reaches a maximum at 2 Hz, and then decreases, indicating maximum impact at 2 Hz.

In Fig. 15, the relationship between the mean values of peak toe clearance, impact ratio, and contact ratio obtained in the current study is depicted. The figure shows the best quadratic fits for peak toe clearance vs impact ratio and peak toe clearance vs contact ratio, as well as the best linear fit for impact ratio vs contact ratio. As anticipated, consistent with previous research on non-vibrating surfaces [1,9,19], the mean

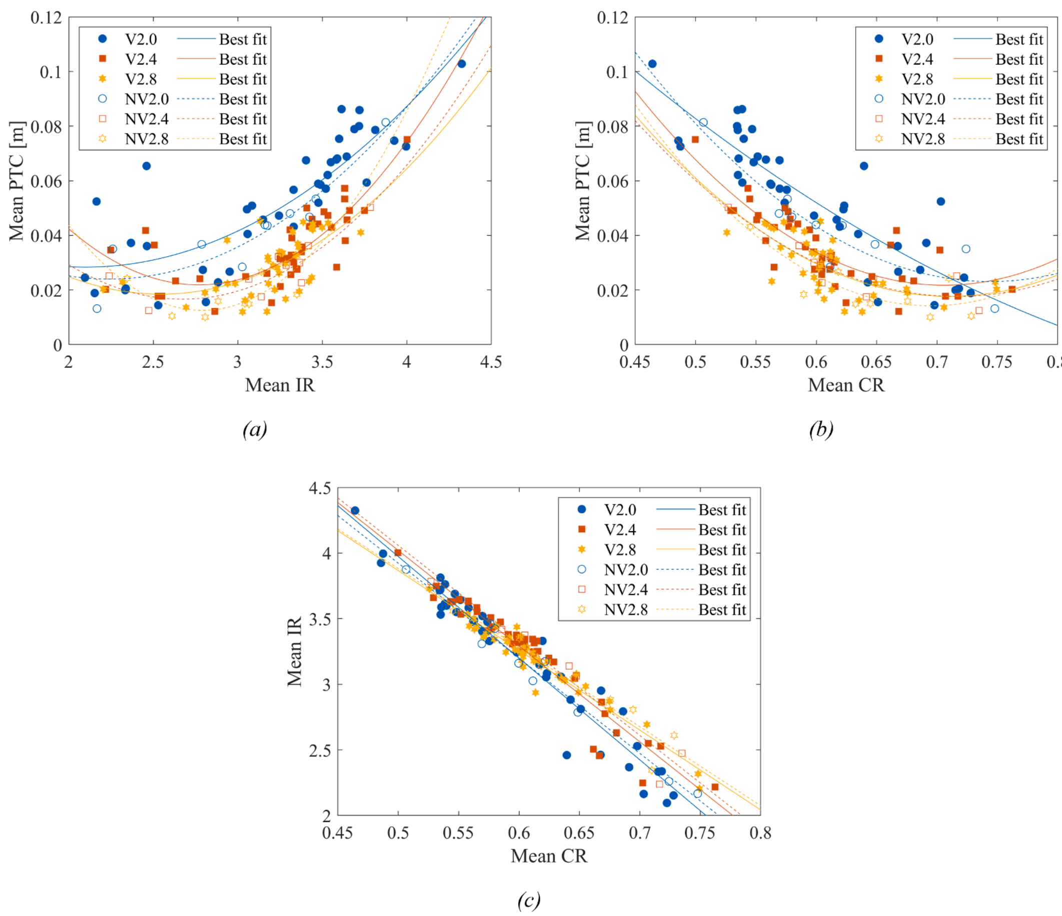

Fig. 15. Correlation between (a) peak toe clearance (PTC) and impact ratio (IR), (b) PTC and contact ratio (CR), and (c) IR and CR for non-vibrating (NV) and vibrating (V) conditions.

peak toe clearance and impact ratio were positively correlated with each other (Fig. 15a) and negatively correlated with the contact ratio (Fig. 15b, Fig. 15c), for both vibrating and non-vibrating platforms. The correlation patterns between these parameters were similar for vibrating and non-vibrating platforms, except at 2.8 Hz. NV2.8 in Fig. 15a is slightly different from V2.8 and other cases. It is important to note that achieving the target frequency was particularly challenging in this specific case (Fig. 10).

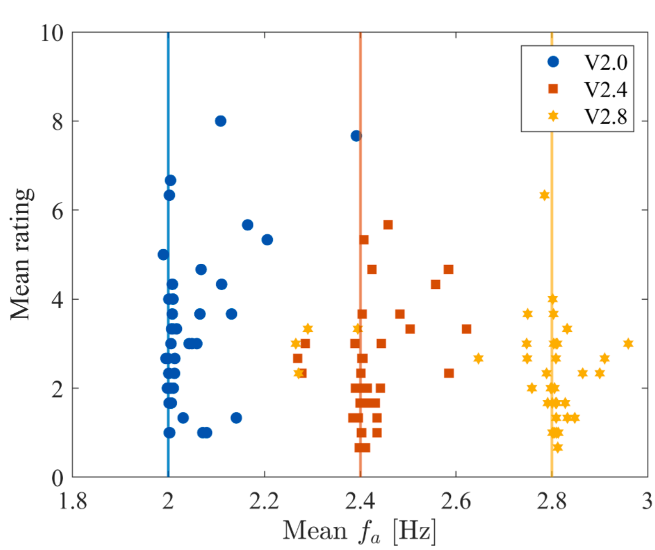

Fig. 16. Mean subjective rating versus mean frequency of jumping.

Jumping at 2.4 and 2.8 Hz with the same peak toe clearance as at 2.0 Hz resulted in higher force generation (Fig. 15a) and shorter contact duration (Fig. 15b) on both vibrating and non-vibrating platforms. Furthermore, the variability of the mean values of all three parameters decreased with increasing frequency. It is worth mentioning that in the tests, the generated force, jump height, and contact ratio were not directly controlled.

4.3.3. Range of values

According to the literature, the mean impact ratio varies between 2.4 and 4.0 on non-vibrating surfaces [1], and the range of impact ratio on vibrating surfaces lies between 1.8 and 4.0 [5]. In this study, on the non-vibrating surface, the mean impact ratio ranged from 2.17 to 3.88, while on the vibrating platform, it ranged from 2.10 to 4.32 (Fig. 15a), aligning with existing literature. The mean peak toe clearance ranged from 0.01 to 0.08 m on the non-vibrating platform and 0.01 to 0.10 m on the vibrating platform (Fig. 15a). Moreover, reported ranges for contact ratio are 0.5 to 0.8 [1] and >0.4 [18] for jumping on non-vibrating surfaces. For jumping on vibrating surfaces away from resonance, the range is 0.5 to 0.7, with an increase near resonance [5]. These ranges are consistent with Yao et al.'s [9] finding that the contact ratio remains above 0.5. In this current study, the mean contact ratio values ranged from 0.51 to 0.75 on the non-vibrating platform and from 0.46 to 0.76 on the vibrating platform (Fig. 15b), in line with prior research. Furthermore, when jumping on the vibrating platform, the upper limits of mean impact ratio and toe clearance ranges were higher, whereas the lower limit of the mean contact duration range was lower compared to jumping on the non-vibrating platform.

4.4. Objective versus subjective response

On the non-vibrating platform, all ten TSs reported a vibration rating of zero for jumping at all three frequencies. Fig. 16 illustrates the mean rating given by each TS for jumping on the vibrating platform, obtained from three trials of the same configuration. The mean frequency of jumping was plotted against the corresponding mean rating. The highest rating of 8 was assigned for jumping at 2.0 Hz, while ratings fell below 6 for jumping at 2.4 Hz. For jumping at 2.8 Hz, the maximum rating was 4 when excluding an outlier rating above 6. Trials resulting in higher subjective ratings were associated with decreased comfort and exhibited greater deviation from the target frequency. This suggests a positive correlation between subjective discomfort and deviation from the target frequency.

The subjective rating for jumping at higher frequencies generally tended to be lower than at lower frequencies, indicating that TSs perceived the vibrations and adjusted their jumps to enhance comfort at that specific jumping frequency. This adjustment involved adopting a preferred timing. While a previous study [20] reported that a person must be stationary on a structure to perceive vibrations, another study [21] argued that individuals' perception of vibrations depends on vibration and activity characteristics. The current findings demonstrate that the TSs modified their jumps upon perceiving vibrations, resulting in reduced sensation when jumping at higher frequencies.

5. Conclusions

This study investigated the effects of vertical vibrations on rhythmic jumping. Results revealed challenges in exceeding 2.4 Hz on non-vibrating surfaces due to frequency precision difficulties. However, jumping on vibrating platforms resulted in consistent frequency accuracy at 2.0, 2.4, and 2.8 Hz, suggesting potential synchronisation with faster audio cues on lively structures. On vibrating platforms, participants adjusted their timing for take-off during downward motion and from a higher position, effectively leveraging vibrations for rhythmic jumping. This adjustment was most pronounced at 2.8 Hz. Notably, participants perceived vibrations as least noticeable at the highest frequency, indicating timing preference for comfort. Additionally, preferred timing on vibrating platforms led to increased toe clearance, impact ratio, and shorter contact duration compared to non-vibrating platforms. This implies that load models developed using jumps measured on non-vibrating platforms may underestimate structural responses.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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