Chapter 31
Evaluating Rhythmic Jumping on Vibrating Platform Using Kinematic Data

Nimmy Mariam Abraham, Genevieve Williams, and Stana Živanović

Abstract Rhythmic jumping can be expected on grandstands during music and sports events and imparts dynamic load on to the structure. This often results in safety and serviceability concerns. Human interaction with vibrations is the key aspect that influences both human and structural response and therefore evaluating this interaction is important. To this end, this paper has compared four methods of analysing rhythmic jumping on vibrating structures using kinematic data. Vector coding method was found to be the most informative. The original vector coding procedure has been modified in this paper to propose a new strategy for classifying the coordination patterns between feet and platform motion. The method can be used to evaluate whether a jumper can achieve a target frequency and target timing of the jumping as well as to quantify the variability in jumping over time. In addition, the method enables quantification of duration of contact phase of a jumping cycle.

Keywords Rhythmic jumping · Vertical harmonic vibration · Kinematics · Vector coding · Coupling angle

31.1 Introduction

Rhythmic jumping occurs when a person alternates between contact and flight phases at a given frequency. It is one of the most common activities during music and sports events on grandstands. People jumping generate larger dynamic force than other human activities including walking, dancing, stamping, hand clapping, swaying, abrupt rising, standing and bobbing. A recent example of a partial collapse of the football stadium in the Netherlands, amid crowd celebrations in response to players jumping in celebration on the pitch [1], is an illustration of potential vulnerability of stands to human actions. In many cases, the frequency of rhythmic jumping or one of its integer multiples matches one of the natural frequencies of the structure, causing large vibration response, referred to as resonance. Besides frequency match, the severity of vibrations depends on human-structure interaction (HSI) and the liveliness (i.e. proneness to vibration) of the structure [2]. The HSI here refers to adaptation of the human kinematics (i.e. body motion) and the resulting ground reaction force (GRF) to the structural vibration and impact of this adaptation on structural behaviour. This paper investigates the adaptation of human kinematics while rhythmically jumping on a vibrating platform. Specifically, the coordination between feet and platform movement is analysed for four scenarios at which the human targeted landing on the platform at different platform positions in the vibrating cycle. This study identifies and compares different methods for analysing rhythmic jumping activity on vibrating platforms.

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31.2 Test Details and Data

Tests were conducted at the VSimulators, i.e. the motion platform facility of the University of Exeter. The test set up includes VSimulators platform into which AMTI force plates are embedded and an OptiTrack motion capture system consisting of a system of cameras. Test subjects (TSs) were asked to jump rhythmically on the platform at specified target frequencies for conditions of vibrating and stationary platform. Platform vibrations were vertical and harmonic with specific vibration parameters (e.g. frequency of 2 Hz and amplitude of 2 m/s^2). To facilitate recording of body motion, the TSs were required to wear motion capture suits on which reflective markers were attached. Conventional full body marker set comprising of 39 markers was adopted. Additionally, four markers were placed at the four corners of the platform to enable recording of platform motion. Kinetic (i.e. GRF) and kinematic data (i.e. marker trajectories) were collected of which only the vertical displacement of the left toe marker and one of the platform markers are analysed here. The test series involved rhythmic jumping by 10 test subjects on vibrating and stationary surfaces. A TS photographed during one of the trials is shown in Fig. 31.1. The data from tests performed by TS4 are analysed here.

TS4 was 24 years old, male, 182 cm tall, had body mass of 65.8 kg and stated that he exercised about 6 hours per week and was not prone to motion sickness. The TS was asked to perform jumping on the vibrating surface at a metronome controlled jumping frequency of 2 Hz. The platform's vibration magnitude was 2 m/s^2, and vibration frequency was 2 Hz. The TS was instructed to land at specific time instances in vibration cycles of the platform. These were landing on the platform while at its (i) lowest position in the vibrating cycle (trough), (ii) reference position and on the way up (mid-up), (iii) highest position (peak) and (iv) reference position and on the way down (mid-down). The target timing instance was presented to the TS through a metronome beat. The timing of the beat for the four cases is visualised in Fig. 31.2. The duration of each trial was set based on the target jumping frequency to accommodate 40 cycles of jumping.

The raw displacement data were low pass filtered using a fourth order zero phase Butterworth filter with a cut off frequency of 10 Hz. The first 10 cycles of jumping in each test were excluded from the analysis so that only steady-state action of the TS is considered.

31.3 Analysing Rhythmic Jumping on Vibrating Platform

A cycle of rhythmic jumping consists of a flight phase that occurs between take-off and landing and a contact phase that occurs between landing and take-off. During the contact phase, load is exerted on the structure through feet contact with the platform. If vibration is present, the jumper's feet get driven by the platform until the take-off. This results in the adaptation of toe movement based on the target timings for landing on the platform. Hence, jumping on a vibrating platform differs from that on a stationary platform. Given that the toe displacement gets adapted based on the target timings for landing on the platform, an important question is whether a jumper can achieve a target set in terms of frequency and timing of the

Fig. 31.1 TS jumping on VSimulators platform

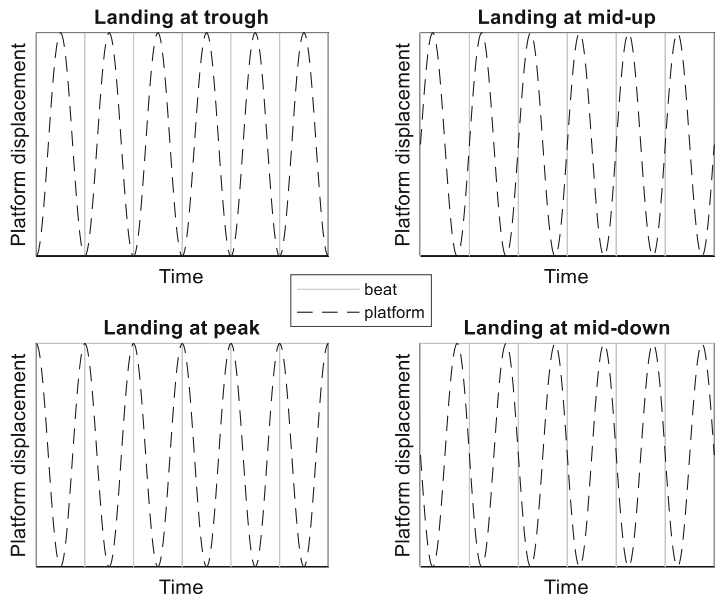

Fig. 31.2 Four cases of target timings for landing on the platform

jumping. Quantifying the variability in jumping over cycles and estimating the duration of contact phase where loading on the supporting structure happens are also significant. To address these intricacies, four methods of analysis are employed and compared. The first method is based on qualitative comparison of time histories. The second is discrete relative phase (DRP), which considers discrete variables to analyse every vibration and jumping cycle. The third method looks at the correlation between platform and toe motion via displacement-displacement plots. Finally, the fourth method uses the vector coding technique to present coupling angle between platform and toe displacements.

31.4 Qualitative Comparison of Time Histories

The most direct way to compare the kinematic data is to visualise the time histories of the signals of interest. Figure 31.3a shows the vertical displacement of toe marker and the position of platform while the TS jumps at 2 Hz on a stationary platform. The timing of metronome beats is indicated for reference. As it is cumbersome to extract information from this representation, the same data is plotted in Fig. 31.3b on a cycle-by-cycle basis. Landing, take-off, contact phase and flight phase are also indicated.

The cycle-by-cycle representation allows qualitative understanding of variability over cycles from the spread of the displacement profile across the cycles. The achievement of target frequency can be qualitatively assessed from the time of occurrence of a specific event, for example the peak displacement across the cycles. The achievement of target timing for landing on the platform can be visualised by comparing the shape of the displacement profiles of platform and toe. This is relevant for a vibrating platform, where a displacement profile exists. The flight and contact phases can also be observed from Fig. 31.3b. Figure 31.4 shows the time history of toe and platform displacements on a cycle-by-cycle basis for jumping under vibrations at four target timings. It can be seen that the TS landed approximately a quarter of cycle earlier than the beat at all four target timings. Variability in jumping across cycles can be assessed, and success in achieving target frequency and target timing can be evaluated from the plots in Fig. 31.4. The shape of the toe displacement profile during contact phase is distinct for each target landing timing while jumping on vibrating platform. The adaptation of toe motion in the contact phase can be visualised by comparing them with the displacement profile on stationary profile in Fig. 31.3b. Figure 31.4 indicates that the variability of contact phase across vibration cycles is low compared to that in flight phase in all the cases shown here. While this qualitative insight is useful, it neither quantifies the coordination between platform and jumping, nor its variability.

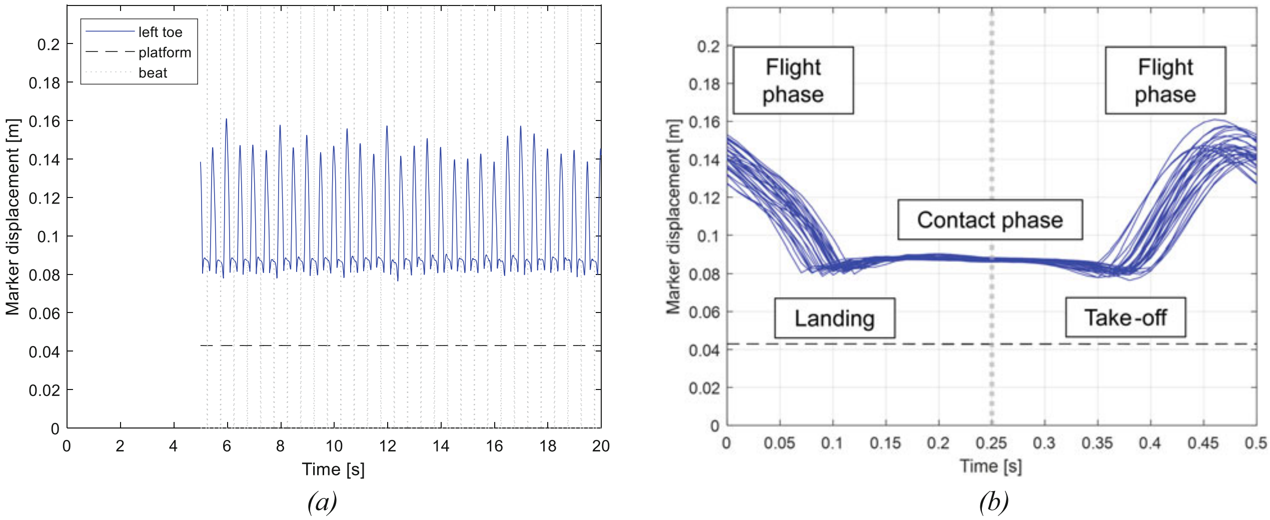

Fig. 31.3 Toe displacement (blue continuous) and platform position (black dashed) for jumping on stationary platform (**a**) Time history (**b**) Time history on a cycle-by-cycle basis (grey dotted pointer indicates the timing of metronome beat)

31.5 Discrete Relative Phase (DRP)

DRP represents cycle-by-cycle time delay (latency) of an event in the motion of a segment with respect to the motion of another segment [3]. In the present context, the segments are platform and toe. The peak displacement of each cycle is used as the event to evaluate DRP as

$$\mathrm{DRP} = \frac{(t_2 - t_1)}{T} \times 360^\circ \tag{31.1}$$

where t_1 is time to peak platform displacement, t_2 is time to peak toe displacement and T is the period of the platform's vibration cycle. The variation of DRP between toe and platform displacements across cycles while jumping under vibrations at four target timings is shown in polar plots in Fig. 31.5. A DRP of 90° indicates landing at the trough position of the platform. DRP is 180° for landing at mid-up, 270° for landing at peak and 0° for landing at mid-down positions of platform. Note that the TS landed approximately a quarter of cycle earlier than the target in all four cases. An example of inconsistent landing timing can be seen in Fig. 31.5d. This method has the merit of quantification of target achievement over the qualitative results obtained from the previous qualitative comparison. However, the quantification is with respect to a discrete event during a vibration cycle, which therefore does not provide insight into the adaptation of toe motion during a vibration cycle. The information on flight and contact phases and coordination during a cycle except during the chosen event cannot therefore be obtained.

31.6 Qualitative Comparison of Displacement-Displacement Plots

This method involves plotting platform displacement against toe displacement and observing the correlation between them. This is similar to time history method, but the information on both the displacements are combined into a single plot rather than separate plots. The correlation between toe and platform displacements across cycles while jumping under vibrations at four target timings is shown in Fig. 31.6.

The plots provide qualitative information on target achievement and the phases in a cycle. The spread in the graph represents variability across cycles. A unique feature that contains information on platform-activity correlation is the slope of the graph. A positive slope indicates a positive correlation where both the platform and the toe move in the same direction, either up or down. A negative slope shows a negative correlation where the platform and the jumper move in the opposite directions. The contact phase is separated from the flight phase by a positively sloping region with low variability across cycles. In Fig. 31.6a, the correlation is positive throughout, with regions of two different slopes for contact and flight phases.

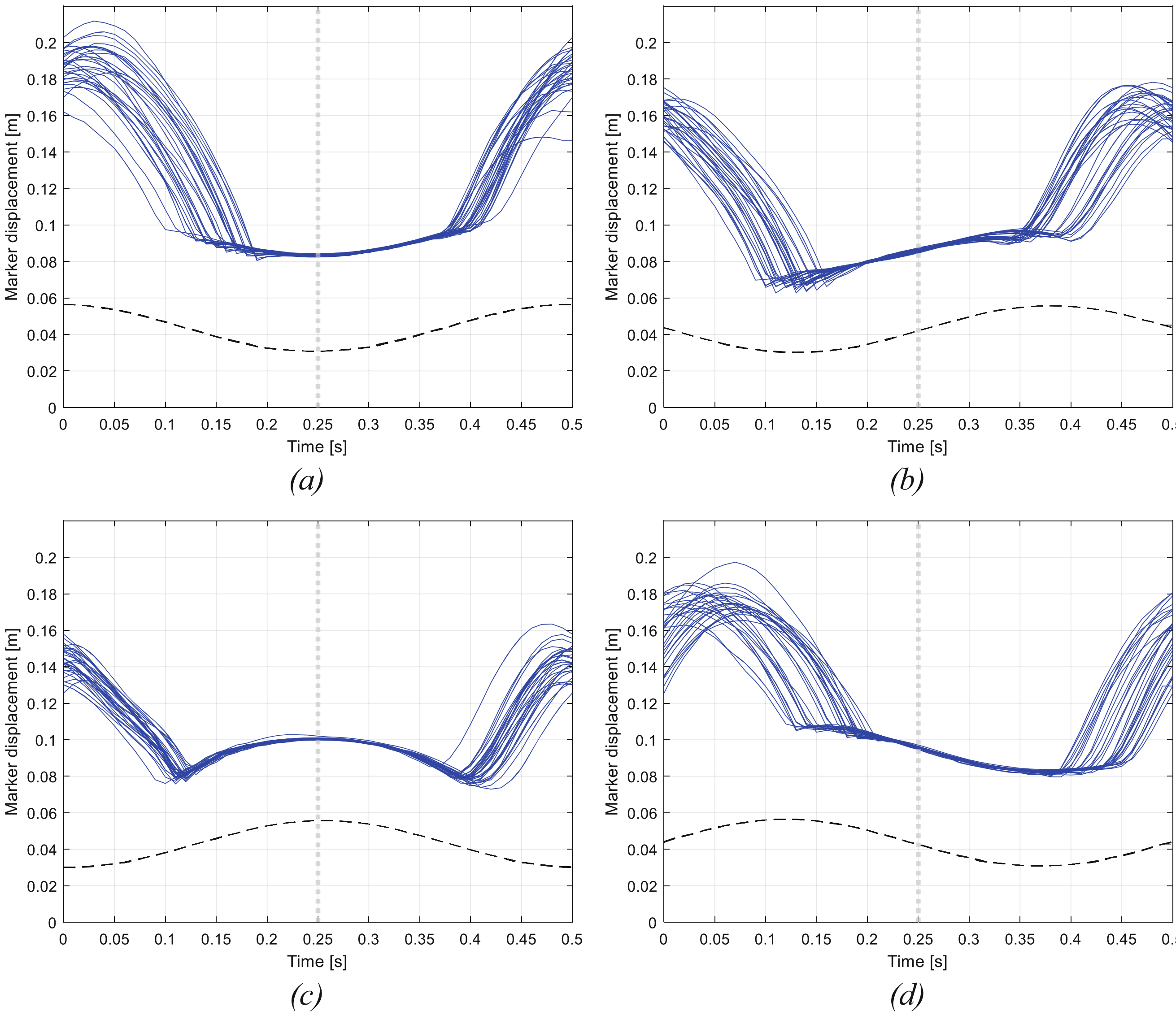

Fig. 31.4 Toe (blue continuous) and platform (black dashed) displacements on a cycle-by-cycle basis for jumping on vibrating platform with target landing at (**a**) trough (**b**) mid-up (**c**) peak (**d**) mid-down positions of platform (grey dotted pointer indicates the timing of metronome beat)

In Fig. 31.6b, the correlation is positive during the contact phase, whereas the flight phase has regions of both positive and negative correlations. In Fig. 31.6c, the correlation is positive in the contact phase and negative in the flight phase. In Fig. 31.6d, the correlation is positive during the contact phase, whereas the flight phase has regions of both positive and negative correlations. Thus, the overall shape of the plots suggests the timings of landing on the platform. The change in correlation during a cycle observed in this representation cannot be captured using the previous methods. Nevertheless, this method provides only a qualitative approach in understanding the coordination between jumping and the platform's vibration.

31.7 Modified Vector Coding

Vector coding is another technique that can be employed to understand the dynamic interaction between platform and toe displacements while jumping on a vibrating platform. In this method, the relative motion between two segments is quantified by calculating the vector orientation between adjacent points, referred to as coupling angle [4–6]. Coupling angle (γ) between

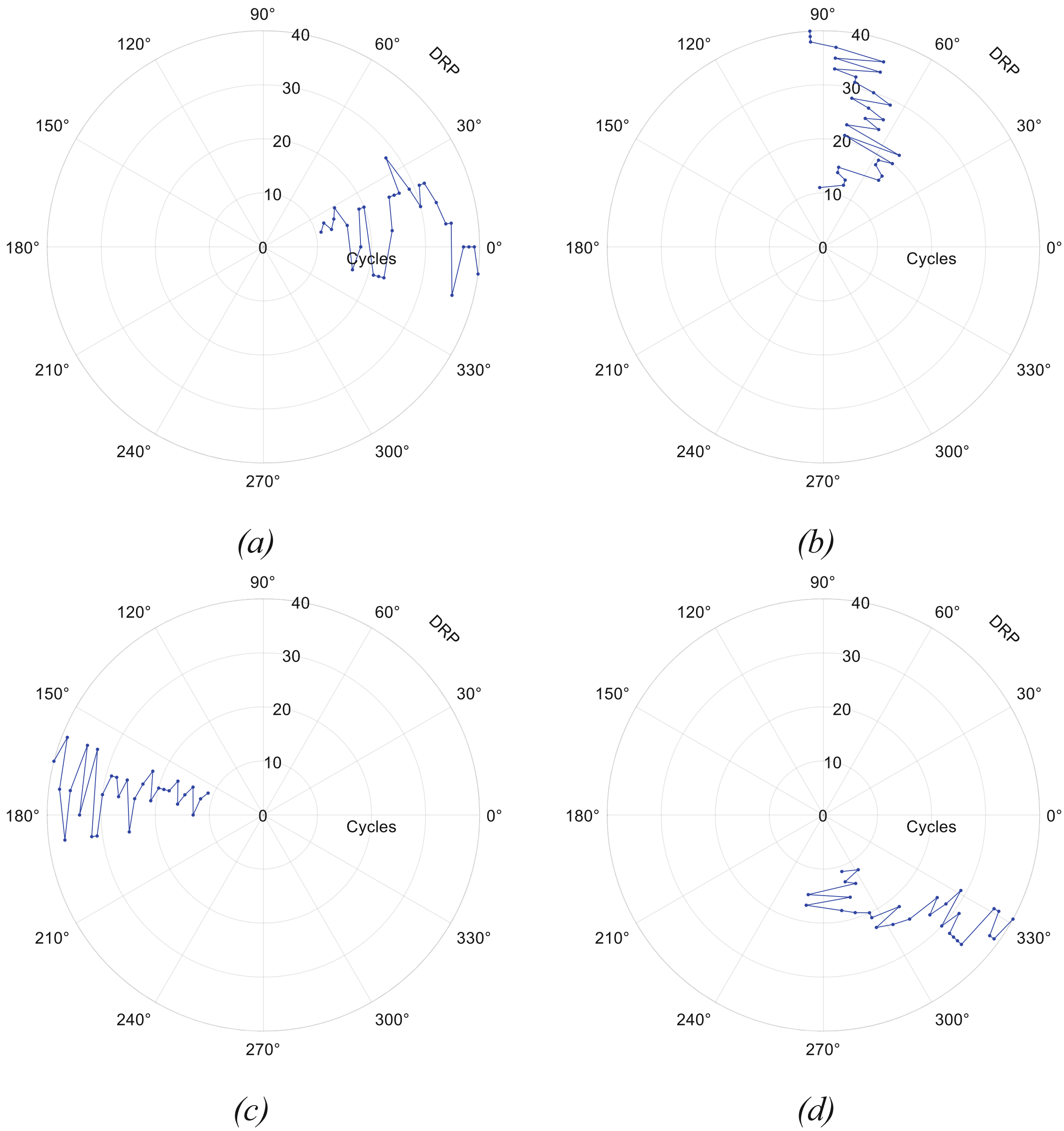

Fig. 31.5 DRP between toe and platform displacements for jumping on vibrating platform with target landing at (**a**) trough (**b**) mid-up (**c**) peak (**d**) mid-down positions of platform

y and x, representing platform displacement and body displacement in this case, respectively, is defined as

$$\gamma = \tan^{-1}\left(\frac{y_{i+1} - y_i}{x_{i+1} - x_i}\right) \tag{31.2}$$

where $i = 1, 2, 3\ldots$ are the instants where the displacements are recorded. Calculation of coupling angle is illustrated in Fig. 31.7. Coupling angle is represented by a value between 0° and 360°. As it is directional, circular statistics can be applied to calculate the mean and variability of multiple cycles of a task like rhythmic jumping. Classification of the coupling angle into distinct classes (bins) based on the pre-defined range in which the angles fall helps to understand movement coordination during jumping. The usually identified four coordination patterns are: in-phase (22.5°–67.5°, 202.5°–247.5°), anti-phase (112.5°–157.5°, 292.5°–337.5°), body-dominant phase (0°–22.5°, 157.5°–202.5°, 337.5°–360°) and platform-dominant phase (67.5°–112.5°, 247.5°–292.5°).

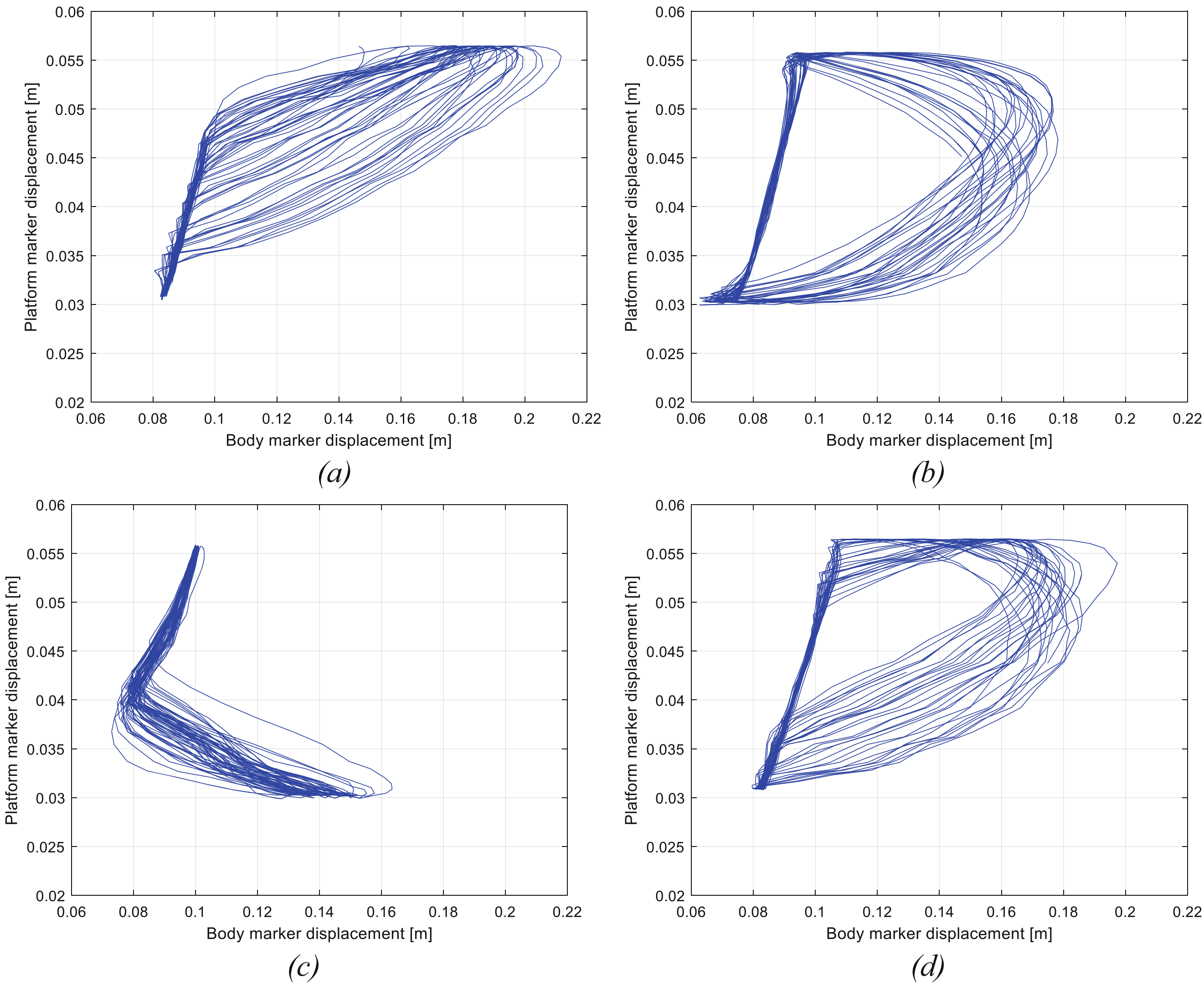

Fig. 31.6 Correlation between toe and platform displacements for jumping on vibrating platform with target landing at (**a**) trough (**b**) mid-up (**c**) peak (**d**) mid-down positions of platform

In this study, the bins are modified based on the ratio of maximum displacements of platform (y_{max}) to that of toe (x_{max}) for each trial. The new bins are flight in-phase and anti-phase (around 0° and 180°), contact in-phase (around 45° and 225°), platform dominance (around 90° and 270°) and anti-phase during transition between phases (around 135° and 315°). The bin edges (b_i) are calculated as shown in Fig. 31.8. This modification allows to negate dominancy of toe displacement over platform displacement and separates out the contact phase from the rest of the cycle. Thus, the ratio of contact phase duration to the time period of the cycle can be calculated from the ratio of population falling in the contact phase bin.

Figure 31.9 shows the polar plots of coupling angle and their respective bins while jumping under vibrations at four target timings for landing on the platform. In Fig. 31.9a, the toe displacement is always in phase with the platform displacement. The contact and flight phases are separated using the modified bins. In Fig. 31.9b and 31.10d, the contact phase is always in phase, whereas the flight phase has both in-phase and anti-phase regions. In Fig. 31.9c, the contact phase is always coordinated in phase in contrast to the anti-phase coordination of the flight phase. Thus, the adaptation of toe motion while jumping at four target landing instances is quantified through binning of coupling angles. The percentage duration of contact phase are 26.9, 27.8, 36.9 and 32.9 for target landing at trough, mid-up, peak and mid-down, respectively. This does not include the duration of landing and take-off. The contact duration is minimum when the target landing is at the trough and maximum when it is at the peak of the vibration cycle. Figure 31.10 shows the coefficient of variation (CoV) of coupling angle between toe and platform displacements across cycles at the four target timings for landing on the platform. CoV indicates the variability across cycles of jumping at instances along cycle. Variability is high during change in direction of

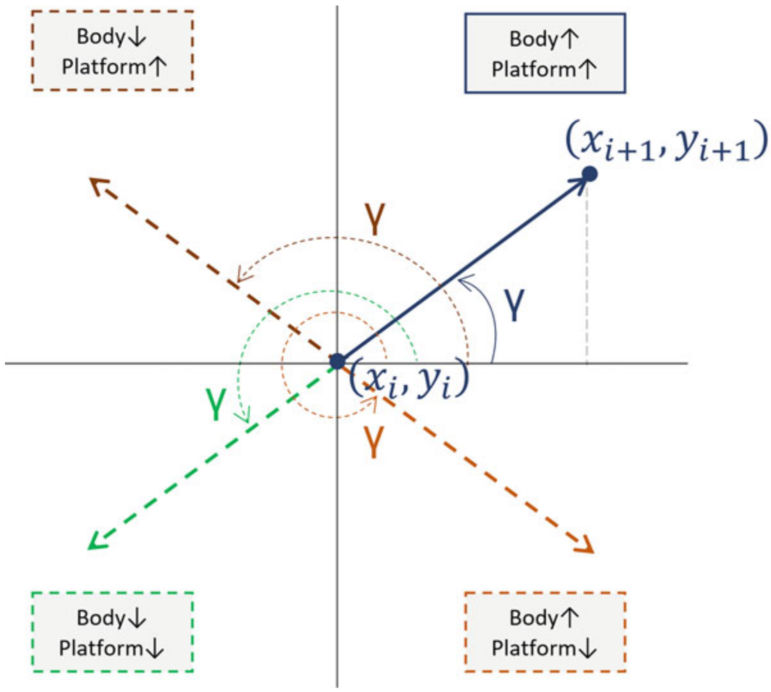

Fig. 31.7 Calculation of coupling angle for different coordination patterns

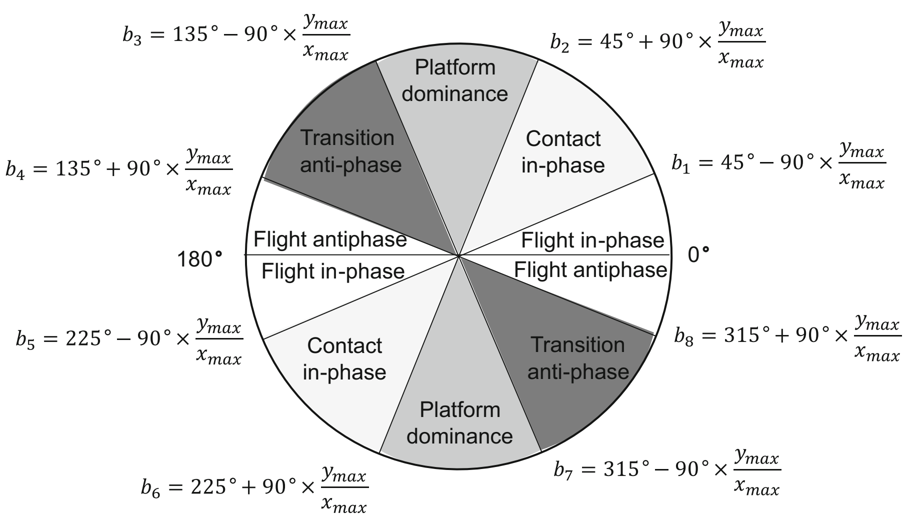

Fig. 31.8 Modified definition of coupling angle bins

toe motion, i.e., during landing, take-off and at peak displacement. At these instances, the coupling angle shifts across bins leading to higher variability at transitions. The variability is in general low during contact phase.

31.8 Comparison and Discussion

Some aspects of rhythmic jumping have been analysed using qualitative comparison of time histories, DRP, qualitative comparison of displacement-displacement plots and modified vector coding. The methods using time histories and displacement-displacement plots provide qualitative insight into events during a jumping cycle and across all cycles in a trial. The adaptation of toe displacement in the contact phase is observed and the variability across jump cycles is qualitatively assessed. Using DRP method, the latency of peak displacements between platform and toe was calculated,

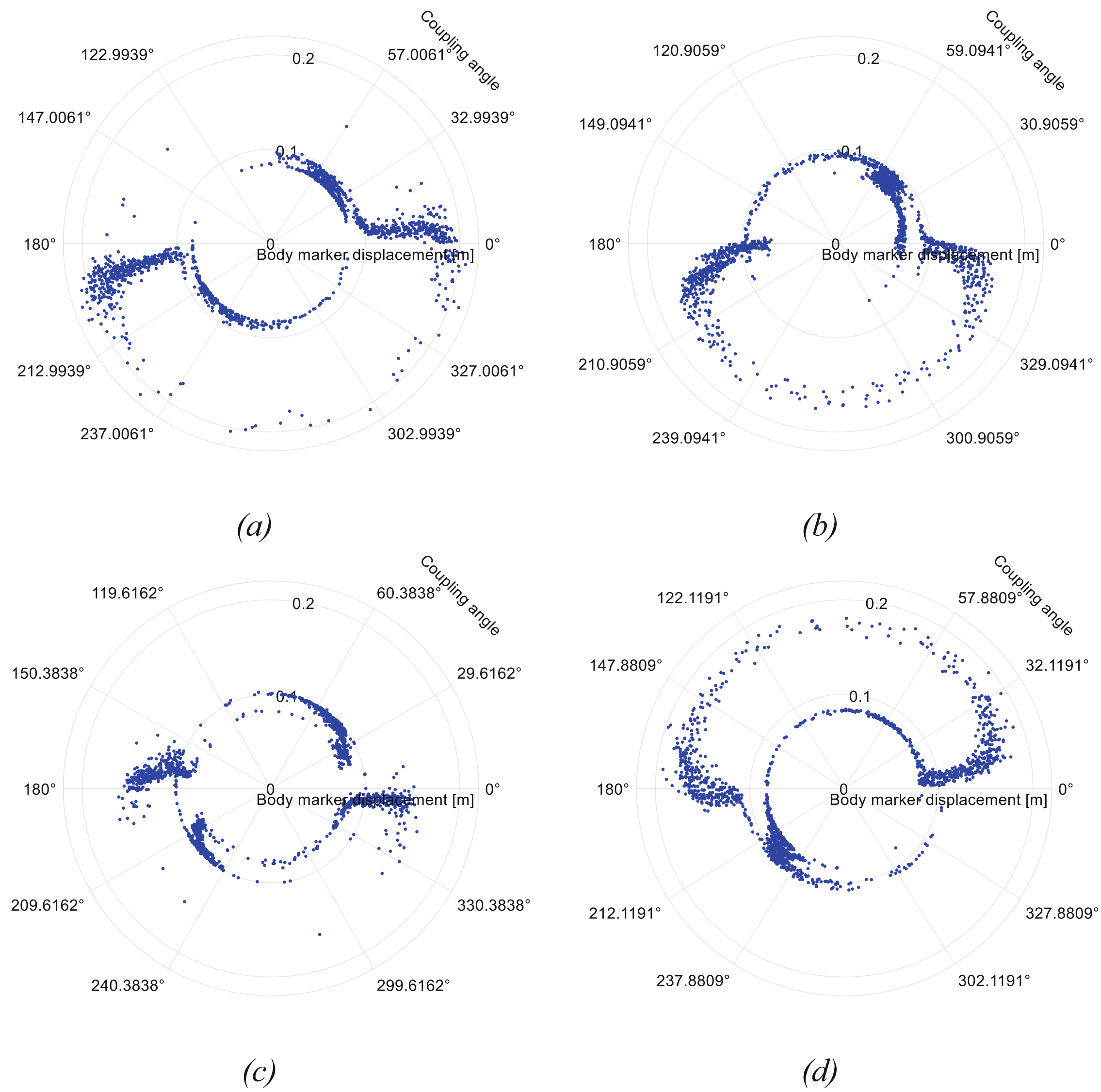

Fig. 31.9 Polar plots of coupling angle between toe and platform displacements (angular axis) against toe displacement (radial axis) for jumping on vibrating platform with target landing at (**a**) trough (**b**) mid-up (**c**) peak (**d**) mid-down positions of platform

which enabled assessment of target achievement. However, this method is based on one discrete point in a cycle only. Vector coding technique is employed to evaluate the coordination between platform and toe motion by calculating coupling angles throughout jumping cycles. A modified binning strategy for coupling angle is adopted to classify the instants during a jumping cycle into contact and flight phases. This allowed systematic verification of target achievement based on expected coordination patterns for a given target timings for landing on the platform. The CoV of coupling angles revealed the variability of toe displacement across cycles of jumping. Furthermore, the duration of contact phase is calculated as a percentage of total duration of the jumping cycle. Thus the modified vector coding technique proposed in this paper is a powerful method for analysing rhythmic jumping under vibrations. All the methods reviewed here are entirely based on kinematics, thus can be adopted for field tests by using one or few inertial measurement unit(s) placed at representative body landmarks. Finally, this study shows that toe displacement is an informative variable that can be used to extract knowledge on HSI during jumping. The reason is that the toes are in direct contact with the platform, thereby being the most influenced part of the body.

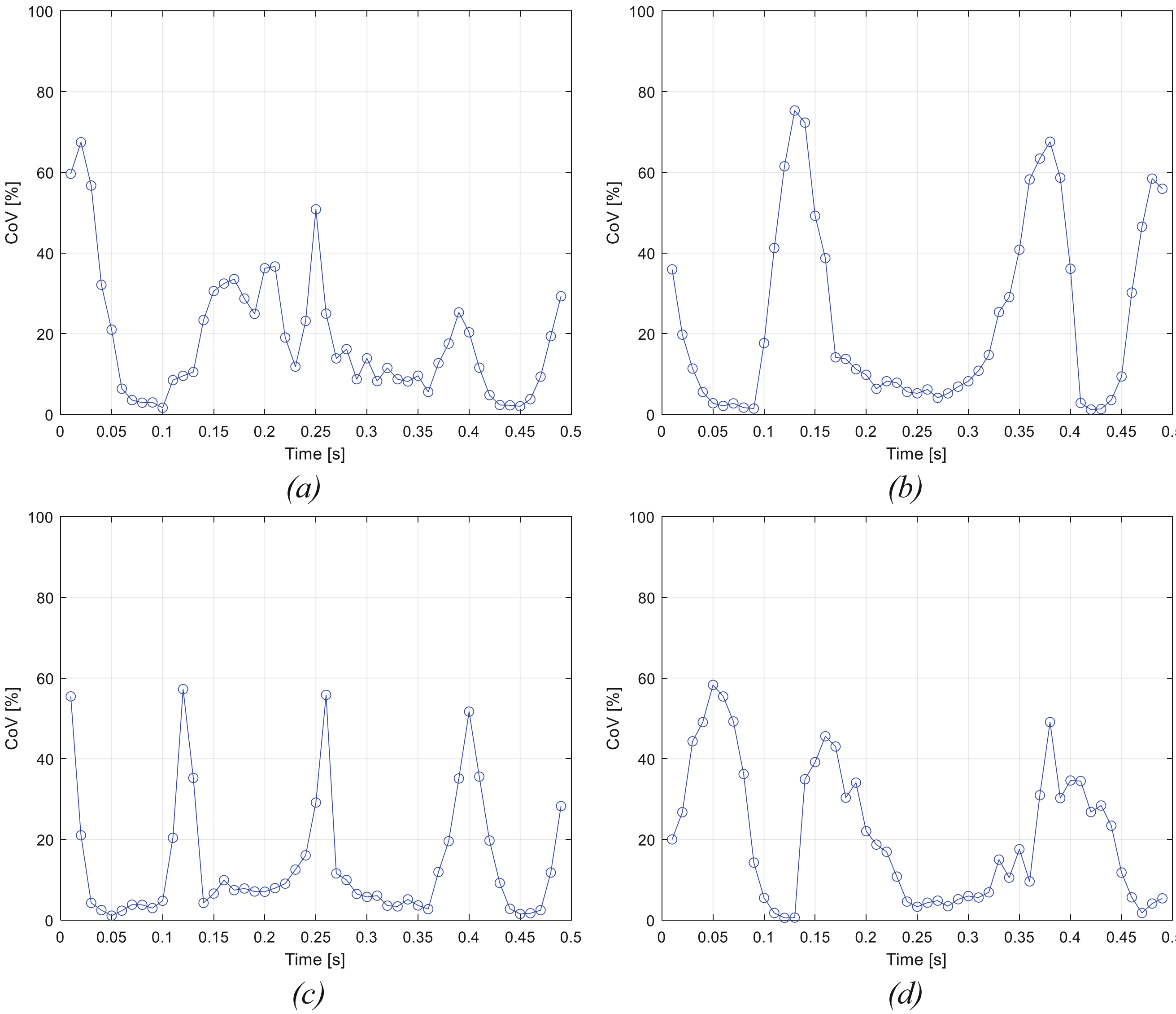

Fig. 31.10 CoV of coupling angle between toe and platform displacements across cycles for jumping on vibrating platform with target landing at (**a**) trough (**b**) mid-up (**c**) peak (**d**) mid-down positions of platform

31.9 Conclusion

This study has identified and compared four methods for analysing rhythmic jumping activity on vibrating platforms with emphasis on target timings for landing on the platform. A modified vector coding technique has been proposed and demonstrated for a case where a TS jumped at 2 Hz on a platform, vibrating in the vertical direction following harmonic vibration with frequency of 2 Hz and amplitude of 2 m/s^2. This method provides insights into a jumper's coordination with platform and thus his adaptation under vibrations for target timings of landing at trough, mid-up, peak and mid-down positions of the platform. This is achieved by analysing the coordination patterns of coupling angle based on a novel binning strategy. The CoV of coupling angle indicates the variability in jumping across cycles of a trial. The contact phase of jumping cycle, where loading on the structure occurs, is quantified as a percentage of the duration of the jumping cycle. The duration of contact phase are 26.9, 27.8, 36.9 and 32.9% of vibration cycle for target landing at trough, mid-up, peak and mid-down, respectively. This indicates a shorter contact for target landing at the trough compared to longer contact in case of target landing at the peak of the vibration cycle. Vector coding is identified as the most powerful technique in comparison with other methods based on time history, DRP and displacement-displacement correlation. The future work will include evaluation of the consequence of adaptation of toe displacement in GRF.

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