A New Perspective Analysis of Variations in Cockroach Motion Kinematics Using Precision Kinematic Image Processing

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Abstract

The ability of insects with sticky legs in moving on vertical and horizontal surfaces can be related to adhesion properties of their legs. Despite the key role of the mechanical mechanism of the body and leg movements of insects during adhesion, this mechanism has not been fully still understood. This study aimed at investigating the mechanism of leg movements in movement cycles from the start to restart of the movement of the same leg on a straight path. Irregularity in the acceleration-time graph of the center of mass (COM) can be partly related to this assumption on the sequence difference of leg movements during insect motion. Unlike current assumptions on repetitive movement cycles in the simulation of cockroach motion kinematics, our results revealed a difference in cockroach motion in each cycle. This finding can evolve the mechanism of simulated robots inspired by insects. Due to the low average weight of the American cockroach (0.83±0.5 g), the use of accelerometer sensors leads to measurement errors and deformation of the mechanism. Furthermore, the problem with frame-by-frame image processing time during movement cycles can be solved by the method used in this study.

Keywords: Biomechanics; Acceleration; Cockroach; Insect; Biomimetic; Movement Cycle.

1. Introduction

Vertical force and deformation of the body have been extensively studied (Jayaram and Full, 2016). Walking locomotion of insects with sticky feet on surfaces fundamentally differs from other insects, birds, and mammals (Graham, 1985). Studies on animal movements are of great importance in this sense that they ultimately lead to simulation and optimization through advanced materials such as smart materials (Mehrabian and Yousefi-Koma, 2007). The reaction of the olfactory system of flying insects such as the fruit fly has been investigated by studying attraction to visual features according to behavioral conditions in tracking the source of the smell. Furthermore, simulated robots have been investigated via the results on animal movement mechanisms (Basaeri *et al.*, 2014). In addition, equations governing biological problems should be accurately solved (Khajeh *et al.*, 2010) because sticky feet simultaneously apply force, energy, and brake within each step. Insect morphology and kinematics have been evaluated by a high-speed camera (Hughes, 1952). Behavioral changes in an animal's forward speed were also studied (Delcomyn, 1971, Spirito and Mushrush, 1979). A review was carried out by evaluating animals' locomotion such as horse gallops (Clegg, 2007). Biomimetic dynamics or biomechanical locomotion have received much attention from scholars in this field (Fukunaga *et al.*, 2001).

Numerous studies have been conducted on energy absorption and transfer structures (Holmes et al., 2006, Jindrich and Full, 2002, Koditschek et al., 2004). There are also studies on the slower movement of animals on the ground (Büschges, 2005, Cruse et al., 2007).

Spagna *et al.* (2007) studied the movement of insects on rough surfaces. Recent studies on cockroach movement have led to the manufacture of robots and biomechanical cockroaches (Baba et al., 2010, Camhi et al., 1978, Cowan et al., 2006, Full and Tu, 1990, Jindrich and Full, 2002, Kram et al., 1997, Khajeh et al., 2018). Strategies practiced by animals in response to disturbances have been extensively investigated (Biewener and Daley, 2007, Daley and Biewener, 2006, Full et al., 1998, Kohlsdorf and Biewener, 2006, Watson et al., 2002).

Furthermore, speed-dependent parameters such as the size or the least change in legs have been also studied (Jindrich and Full, 2002, Sponberg and Full, 2008).

Mechanical nervous systems are studied for motion analysis. Moreover, several studies have been carried out on fast nervous feedback motion (Koditschek *et al.*, 2004). Nerve delays in assessing a disorder, engine pattern control, as well as delays in muscle function, have been investigated in power applications. Different models have been used for analyzing experimental results used in manufacturing and simulating robots (Altendorfer et al., 2001, Garcia et al., 2007, Quinn et al., 2003).

Numerous studies have been conducted on motion kinematics using image-processing techniques (Bai et al., 2000, Fontaine et al., 2009, Spence et al., 2010, Wu et al., 2015). Studies on the forward speed of animals date back to several decades ago (Delcomyn, 1971, Hughes, 1952, Spirito and Mushrush, 1979).

Movement variations have been analyzed by studying body parts and examining their impact on the movement frequency (Andersen, 2003, Ridgel et al., 2001).

In addition, numerous studies have focused on measuring the power of legs in the six-foot model (Kubow and Full, 1999). Behavioral observations in the open environment have been carried out by searching for trotting and ambling gaits (Bender *et al.*, 2011).

A similar trend of step reduction with frequency was observed by investigating the motion plan of animals with different morphological characteristics such as the geometry of legs, body and skeletal structure (Full et al., 1989, Kubow and Full, 1999).

The force applied by the legs was studied in three different modes of legs movements designated as Left 1, Right 2 and Left 3. For this purpose, special tools and ideas were specifically developed for leg movements. In addition, the status of each leg studied by tracking the movements of cockroach with different ages and genders were somewhat predictable. To the best of our knowledge, all cases referred to in this study are novel and can have an important influence on the study of animal life as well as dynamic simulation and design of robotic systems.

This study aims at addressing the following question: Is the previous idea of a repetitive movement cycle of cockroach true, or other cycles can be extracted for the movement of this insect with sticky legs?

2. Materials and Methods

Animals

This study was carried out on adult *Periplaneta* Americana L cockroaches capable of normal flight. The cockroaches of both genders with an average weight of 0.84 g (N=13) were selected for the experiments. All animals were designated by numbers. Experiments were carried out during the daylight period at an ambient temperature of 23.0 ± 2°C.

Track with Compliant Substrate

Two glass strips were used on both sides of the movement path, as the cockroach could not leave the Video Axis. The system was capable of changing the angle without removing the video equipment. A Canon 240 camera and two Samsung 120 fps cameras were used to record videos of the cockroaches. For this purpose, two high-resolution cameras were installed in both vertical and horizontal directions and a camera was also installed in the upper part of the treadmill (Figure 1).

Each test (trial) was recorded at shutter speeds of 400, 240, and 120 fps. High-resolution speeds of 240 to 400 fps and 120 fps were used due to the lower resolution of videos recorded at a shutter speed of 400 fps.

Experimental Setup

The experimental setup consisted of a 100 cm×120 cm table hinged on a same size screen capable of changing the angle of slope up to80˚±0.2. Figure 1 schematically shows the device during the angle shift. Three parallel treadmills on the table are part of a CNC machine. Three tiles with different hardness and designs quickly compared different designs after each break between the cockroach movements or the hard tile changed the position of the cockroach and the video system on the next treadmill with a different design or hardness. A moving fixture was placed at the top of each bar on which two cameras were mounted perpendicularly. The third camera was installed above each bar to record videos of three angles and three views simultaneously.

The motion system was constructed by a new Japanese CNC device with high manufacturing precision due to manufacturing tolerances, installation, and control system. The system works with a 3A stepper motor and the control board with motor feedback is able to manually control the control panel. It can also be connected to a computer for data logging and control.

The cockroach moves on a 5 cm×70 cm plastic tape made of soft PVC installed on the table. Modulus of elasticity was about 10±0.1 MPa with an approximate hardness of 48±0.5 shore A.

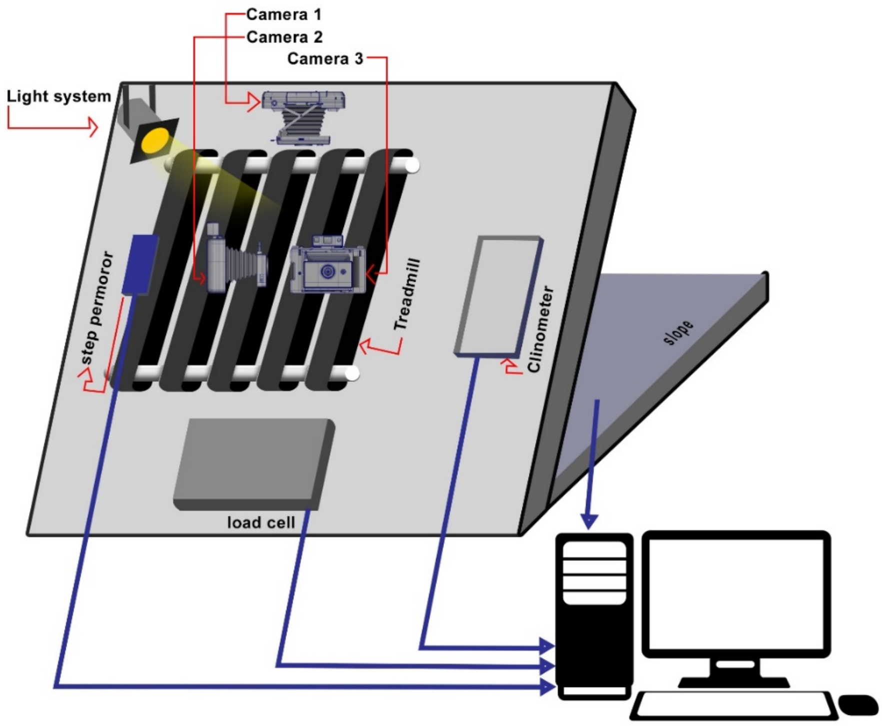

Figure 1. Schematic representation of the experimental setup consisting of three cameras in three perpendicular directions, lighting system, sloping and measurement systems, a dynamometer with a precision of 0.01 gr and four rows of treadmills on which different types of pads (tiles) are installed and a computer processing system to control the input to stepper motor and all outputs. A frequency of 300 pulses per second generated by the engine is much higher than the natural frequency of a cockroach's feet (25 Hz) (Wilson 1965)

Measurement Instruments

The measurement instruments installed on the system include an inclinometer, a hygrometer, and a speedometer. The accuracy of the inclinometer was ± 0.1 while that of the hygrometer and speedometer respectively was ±1% and ±0.1 cm/s as measured by the encoder system of the treadmill.

Lack of Impact of Treadmill Motion on Acceleration

Due to the low speed of the treadmill and the significant difference between treadmill and cockroach leg speeds, the lowest level of sensitivity can be expected in acceleration analysis.

Acceleration Measurement

Acceleration is calculated from equation 1.

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1} \tag{1}$$

Specifically, speed is eliminated from both sides of the above equation. To reduce error, the Gregory-Newton Forward Difference Approach was used for obtaining the acceleration between two points (Eq. 2):

$$f(x) \approx P_2(x) = f_i + \frac{\Delta f_i}{h}(x - x_i) + \frac{\Delta^2 f_i}{2!\,h^2}(x - x_i)(x - x_{i+1}) \tag{2}$$

$$\left.\frac{df}{dx}\right|_i = \frac{\Delta f_i}{h} + \frac{\Delta^2 f_i}{2h^2}(x - x_{i+1}) = \frac{f_{i+1} - f_i}{h} - \frac{f_{i+2} - f_{i+1} - (f_{i+1} - f_i)}{2h} \Longrightarrow$$

$$\left.\frac{df}{dx}\right|_i = \frac{4f_{i+1} - 3f_i - f_{i+2}}{2h}$$

Jerk and snap are calculated from the functions in the following equations:

$$\vec{j}(t) = \frac{d\vec{a}(t)}{dt} = \dot{\vec{a}}(t) = \frac{d^2\vec{v}(t)}{dt^2} = \ddot{\vec{v}}(t) = \frac{d^3\vec{r}(t)}{dt^3} = \dddot{\vec{r}}(t),$$
$$\vec{s}(t) = \frac{d\vec{j}}{dt} = \frac{d^2\vec{a}}{dt^2} = \frac{d^3\vec{v}}{dt^3} = \frac{d^4\vec{r}}{dt^4}$$

where $\vec{s}$, $\vec{j}$, $\vec{a}$, $\vec{v}$, $\vec{r}$ and t respectively represent snap (jounce), jerk, acceleration, velocity, position and time.

Selection Criteria

At any stage of comparison, the experimental data were statistically verified and analyzed using the t-test. Due to data normality, two different phases can be reasonably compared. Finally, any stage with a difference of more than 0.05 with two other similar stages was excluded from the single dose tests (a P-value of less than 0.05 resulted in rejection). Comparison of the results in several stages by the Wilcoxon Rank-Sum test led to the same validity (in the case of abnormal data).

According to the selection criteria, four tests were conducted using 13 cockroaches and 3 different angles in 6 steps each time. Of 936 stages, more than 200 were acceptable.

Tracking and Validation

Tracking was carried out manually and using a Kalman filter. A program was written in MATLAB based on the Kalman filter for successful tracking of fixed points marked on the back of the cockroach. However, movement of different parts of the treadmill led to tracking of these points and combining them with the joints of the cockroach's legs. This, in turn, led to the composition and complexity of the tracked images. Therefore, a Kalman filter could not be successfully utilized with a moving treadmill.

Therefore, all points on the back and leg joints of the cockroach were separately tested by three examiners. The tracking process was carried out by two persons and their results were subsequently compared. Tracking of 936 steps by two persons lasted six months. The two reports were compared by a code written in MATLAB for modifying the single mismatch of steps. The comparison method aimed at comparing all nodes in both x and y directions. Any failure to comply with an upper margin of 5% was re-tracked by a third person, and the point was then modified and controlled. The spot was marked with an appropriate symbol in most tracks. In the case where the marking was not previously completed, a spot with a different color was chosen.

Statistical Analysis

Normality of experimental data was evaluated by the Shapiro–Wilk test. The experimental results were processed on a computer using the ANOVA test. Statistical analyses were carried out with the help of SPSS and MATLAB.

Signal Processing

Forward acceleration and yaw angle were measured for analyzing the position of legs. The measurement method presented by Spence *et al.*, (2010) was used for this purpose.

Position and velocities were calculated based on the center of mass on the back of the cockroach. The pitch angle was measured on the z=0 plane. The positive direction x-axis was considered to be along the movement of the cockroach and the yaw angle was also considered to be in the positive direction of the horizontal axis. The positive angle of the roll was determined to be the free state of the cockroach parallel to the treadmill and the trigonometric direction of the x-axis.

Experimental Methods

The experiments were conducted in two modes, namely (1) cockroach movement on the table and a fixed pad, and (2) cockroach motion on a moving pad or treadmill.

The following rules were provided to evaluate the accuracy of experiments and cockroach movement model. These rules are consistent with the basic assumptions used to study the leg movements in forward acceleration.

1. Cockroaches were left free to move, but yaw angles greater than 15 degrees were not used in the analysis to ensure that the cockroach does not aim to turn around or turn back on the track.

2. The movement corridor is on the previous angle and the cockroach does not move forward (slower than the treadmill).

However, other movements such as the struggle of the cockroach at greater angles were also considered for control and lifting.

Results

A total of thirteen cockroaches were tested to ensure the accuracy of experimental results used in the statistical analysis.

Each cockroach moved on a six-step path and the results of each step were compared with each other. Moreover, each six-step experiment was repeated four times.

Modelling

Numerical simulations were carried out using custom-written scripts in MATLAB.

Differential equations were solved by ODE45 and the movement of the center of mass (COM) was tracked using the code for the Kalman filter in MATLAB.

A mechanism was defined for detecting significant differences between the speed of legs and treadmill. According to experimental results, the feet with no force glide on the surface and its relatively quick motion in the video analysis are quite distinct from the locking feet at very low treadmill speeds. A low treadmill speed of about 5±0.1 cm/s was selected in most of the video recordings. High speeds were not considered to investigate the experimental results under the same conditions.

Motion Kinematics Extraction

When the first foot is up, acceleration is positive and increased compared with initial acceleration. Acceleration is positive when Leg 2 is up and Foot 3 starts to move upward. Acceleration is mostly positive to negative when all three legs are up, which is almost negative at that specific time. Maximum acceleration is observed at takeoff with a positive rotation when Feet 1 and 3 from one side and Foot 2 on the other side are locked and the rest of the feet are freely located on the ground. Turning upward starts when Arm 1 is up.

Figure 2 shows the changes in location, velocity, and acceleration along the movement path. However, Figs. 3 and 4 respectively show the location and velocity in a movement cycle (movement of one foot to the repeated movement of the same foot). The results in Figs. 3 and 4 were extracted from Figure 5.

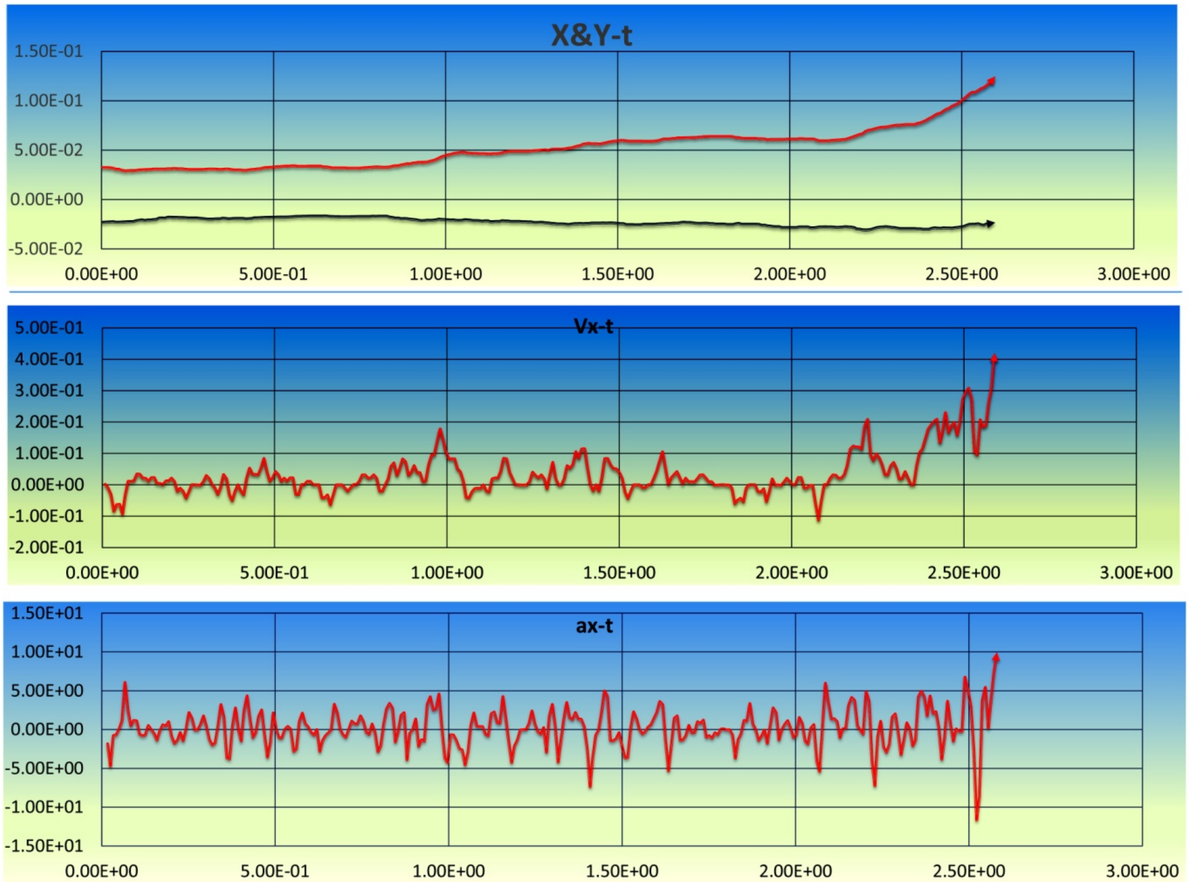

Figure 2. (A) Location-time chart in the longitudinal (X) and transversal (Y) directions (B) velocity-time (V_x-t) chart and (C) acceleration-time (a_x-t) in the entire route of experiment

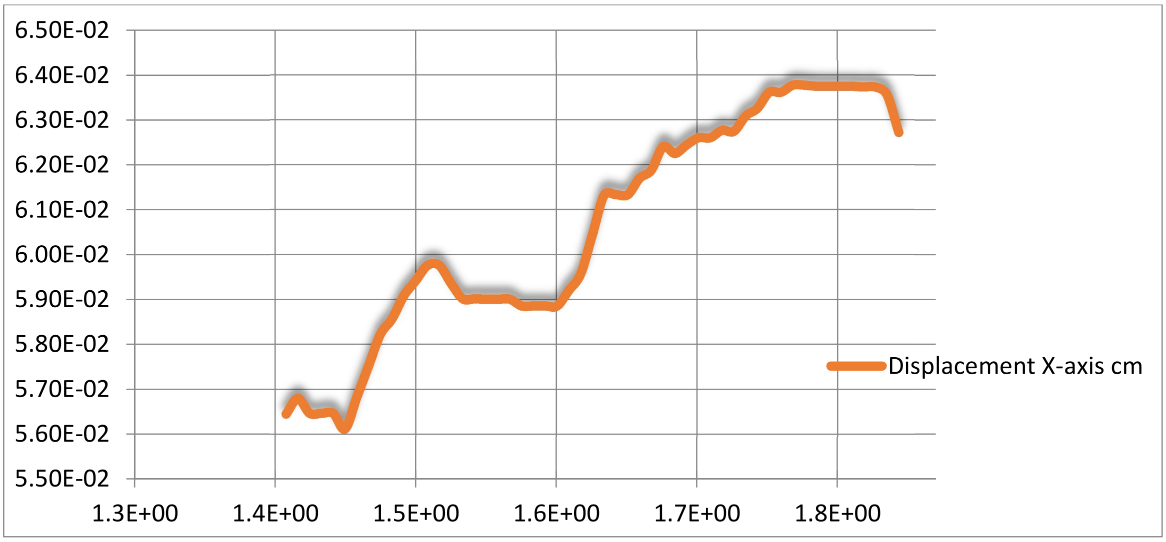

Figure 3. The location-time diagram of a movement cycle (extracted from the results in Figure 2)

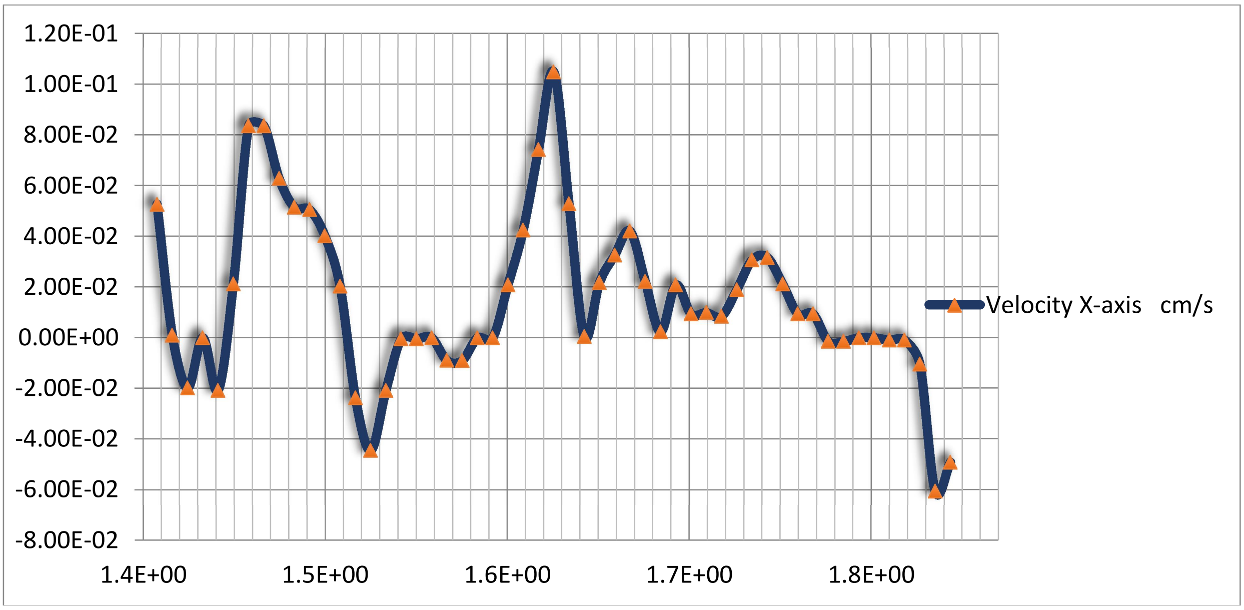

Figure 4. Velocity-time diagram of a movement cycle (extracted from the results in Figure 2)

The Movement Cycle

The movement cycle of a cockroach leg was defined from the beginning by raising the right hand until the moment of repeating this act.

According to the results, the cockroach has different movement cycles in fast and slow movements, and the order of legs with a specified cycle differs from a repetitive cycle. Three different cycles were investigated in this study. Movement order and position of the legs were taken into consideration for analyzing acceleration changes in movement cycles.

As clearly seen in Figure 5, the momentary movement of the insect was recorded with respect to acceleration variations. The results of various cycles showed that the repetitive movement of the left foot, the middle right leg, the last left leg and the right front leg, the left foot of the middle leg, and the last right foot in any direction assumed in previous studies is not repeatable even with a high approximation. Figure 3 shows the motion extracted from the results in Figure 2. Failure to repeat the previous hypothesis was verified through more than 200 tests (ANOVA, P = 0.15).

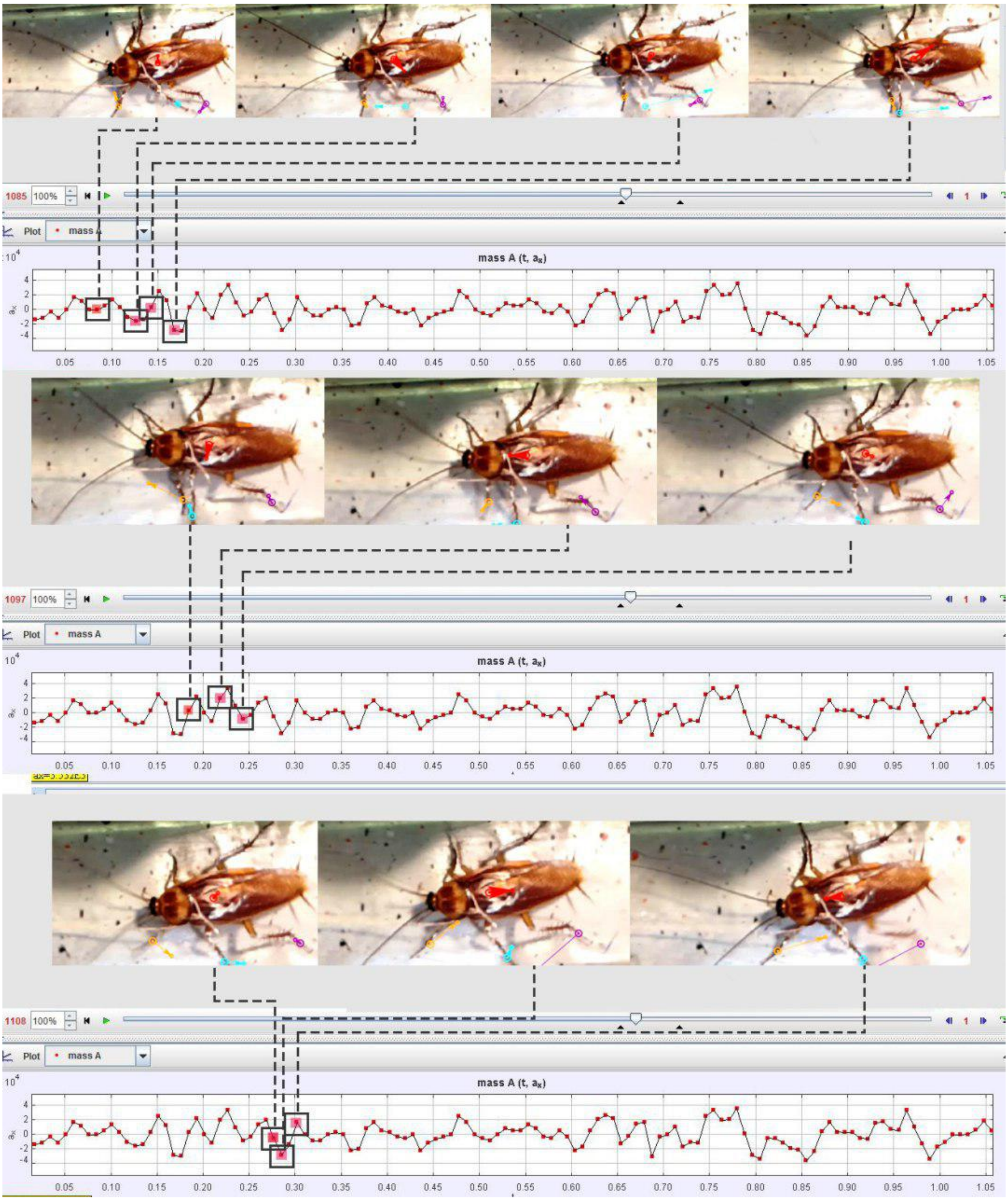

Figure 5. The movement of the cockroach based on the position of legs at different times and changes in acceleration along the longitudinal axis

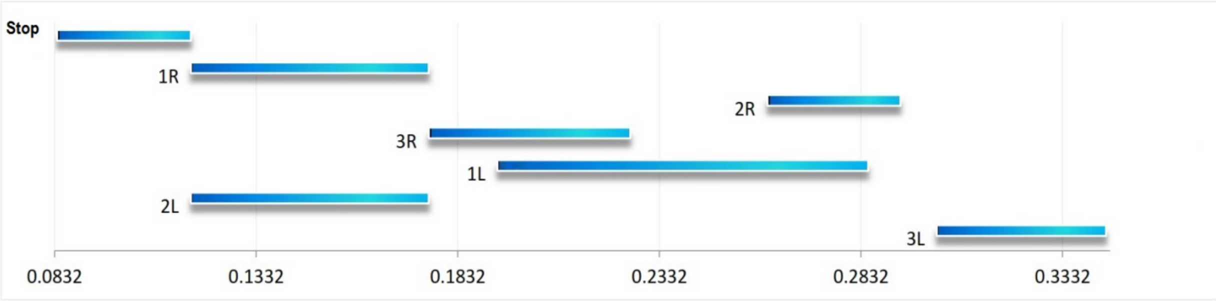

Figure 6. Body movement and the position of each leg versus time indicating the order of the movement of legs and the starting and ending points of the three cycles

Table 1 lists the one-way ANOVA results and compares the average accelerations in each movement cycle. 1.

Table 1. Analysis of variance (ANOVA) for three movement cycles

			Std. Deviation				Median	Half-cycle validation in three cycles ANOVA Test of ax	
Cycle							In 13 Test		
		ax (m/s^2)		ax (m/s^2)		time (s)	ax (m/s^2)	P	F
	1	2.48		2.172		46.8		0.558	0.347
	2	1.36		1.206		48.1	0.054	0.658	0.198
First three right legs	**3**	1.79		1.348		47.6		0.329	0.964
Second three left legs	**1**	1.88		1.607		53.2		0.627	0.238
	2	0.79		1.057		51.9	0.054	0.388	0.753
	3	1.27		0.999		52.4		0.842	0.04

Note:
1. Numbers in parentheses indicate the number of samples used in comparisons.
2. Numbers below the values indicate P-values for comparisons with COM acceleration.
3. Values are presented as Mean ± SD.

Discussion

Numerous studies have been conducted on motion kinematics of cockroaches. These valuable works pave the way for future prospective and developments in this research area.

Most studies on cockroaches have considered a cycle with the order of 1R-2L-3R-1L-2R-3L and the changes in energy, acceleration, kinematics, and dynamics of cockroaches have been analyzed assuming repetition of this cycle. Movement of legs in various modes was analyzed. A movement cycle different from the slow movement of the cockroach was analyzed according to the order outlined in Figure 6. Due to a very low weight of about 0.85 g, the use of sensors (which are at least two to three times heavier than a cockroach) in the largest American cockroaches leads to deformation of the body as well as changes in the nature of legs. In this study, the relationships between location-time and acceleration-time were obtained with high precision by tracking the cockroach legs and center of mass. This allows an analysis of actual leg movement without any change.

The diagram obtained for each movement cycle is another distinct feature of this study. Knowing these two values gives us an insight into insect kinesiology and help us in designing biomimetic robots inspired by cockroaches. Moreover, the movement cycles were compared (Figure 6). Interestingly, the same movement force was obtained per unit time despite differences in leg combinations resulting in movement cycles. These studies are novel given the lack of similar research work and due to their contribution to the development of previously proposed methods. Further, the above-mentioned topics will be discussed in detail.

Movement and movement time, as well as the frequency of cockroach motion, have been extensively investigated (Delcomyn, 1971). Movement mechanisms and forces have been investigated for six legs (Full and Tu, 1990; Full *et al*., 1989). However, hopping has not been studied as part of the movement. Furthermore, certain basic movement cycles and jerk and snap calculations have not been previously taken into account. Leg movement has also been simulated through inverted pendulum modeling (McMahon and Cheng, 1990). Stepping and neural system have been also studied (Ahn *et al.*, 2006; Ridgel *et al.*, 2001; Wilson, 1965; Wilson, 1966).

These studies have mainly focused on the acceleration of the center of gravity and no investigation has been conducted on legs. However, this study investigated step taking modes in addition to the movement of the center of gravity. Most studies in this field are based on the center of gravity and thus have not examined feet movement. However, this study also dealt with steps of the leg while tracking movements of the center of gravity. Consequently, all innovations mentioned in this research work distinguish it from other studies in this field.

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Conflict of Interests and Funding

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