Design of an Instrumented, Modular Insect Arena for Motion Analysis and Measuring Ground Reaction Forces of Small Arthropods

Omar Chahoud (1), Travers Sansom (1,2), Toni Wöhrl (1,2), Sebastian Oberst (1)

(1) Centre for Audio, Acoustics and Vibration, University of Technology, Sydney, Australia
(2) Institute of Zoology and Evolutionary Research, Jena, Germany

Abstract - The measurement of ground reaction forces in small arthropods has significantly advanced our understanding of their locomotion and gait adaptations in various environments and behaviours. Accurate measurements of moving small arthropods with bodies in the milligram range require precise instruments such as a miniature force plate for accurate measurement. A miniature force plate is a miniature tread plate mounted on a suspension structure, equipped with sensors to capture strain, and convert it into normal and lateral force components. Inspired by Reinhardt and Blickhan (2014) this project was aimed to develop an instrumented, modular arena to enhance the use of miniature force plates in arthropod bioassays and to adapt it to be applicable to smaller arthropods than European red wood ant (*Formica polyctena*) as used in previous studies. Also, the experimental setup is sought to be capable of capturing high-resolution images with millisecond precision, synchronised with strain gauge data from the miniature force plate. The arena's narrow structure and removable floor increased the likelihood of leg-plate contact during experiments and facilitates rapid bioassay setup. The synchronised video and signal capture offer potential for advanced calibration methods in the future. The developed arena successfully captured images of small arthropods interacting with the structure, provides detailed top-down and side views of the insect anatomy which will be useful for future morphological studies. With the current setup we show the potential to measure ground reaction forces in arthropods weighing milligrams, providing potentially key insights into the biomechanics and motion of insects, critical for the design of bio-informed micro-robotic systems.

5 INTRODUCTION

The study of insect locomotion and ground reaction forces (GRF) has been of significant interest to engineers and biologists alike and has led to the creation of bioinspired robots with enhanced manoeuvrability over conventional robots (Hernandez et al., 2024; Li et al., 2012; Montagut et al., 2024; Werfel et al., 2014; Xuan et al., 2023; Ortega-Jimenez et al, 2023).

Measuring the GRF of insect legs facilitates the exploration of their locomotion patterns, including weight distribution, propulsion, braking and changing direction, stabilisation and balance through varying environmental conditions or situational context. Reinhardt et al. (2014) used 3D printed force plates, with three strain gauges attached to measure triaxial ground GRF of ant footsteps to determine whether grounded running or climbing is present (Reinhardt et al., 2009). The force plates measured in *x*-, *y*- and *z*- direction and were designed to work in combination with video recordings captured forces generated from a single leg of a European wood ant (*Formica polyctena*)). Through the measurement of GRF and tracking of the ant's stance during locomotion, it was discovered that ants use a 'grounded running' form of locomotion, characterised by whole body running dynamics despite having no 6-leg-aerial-phases (clinging to the substrate), cf. Reinhard et al. (2014b). Oberst et al. (2015) used laser vibrometers recording the bottom of veneer discs to characterize the walking signal of ants through inverse deconvolution using nonlinear filtering and Tikhonov regularisation. Sugimoto et al., (2022) measured the GRF of the take-off displacement from a force plate supported by four springs produced by a fruit fly. Takahashi (2022) conducted a literature study of the different applications and types of MFP technology which has been implemented, comparing Reinhardt & Blickhan (2014) to various other equivalent experiments. Fattoruso et al. (2022) proposes methods to improve the force plate strain gauge technology used in Reinhardt & Blickhan (2014) for the measurement of insects less than 5 mg through different calibration and arena setups. Following Oberst et al. (2015, 2017) and Fattoruso et al. (2022), Sepehrirahnama et al. (2023) designed and numerically simulated via the finite element method a micro-force plate (MFP) theoretically able to measure forces down to 1 μN.

To measure the ground reaction forces of small insects in the milli-newton range or smaller (Reinhardt et al., 2014), sensors and materials or their combination with greater sensitivity and larger specific range than traditional capacitance or piezoresistive force sensors have been developed (Shimazaki et al. 2022; Sugimoto et al. 2022). Microelectromechanical Systems (MEMS) force sensors enable the measurement of these micro-Newton forces by detecting voltage changes, thereby providing precise data on insect locomotion (Adam et al. 2024). Other than that, conventional strain gauges supported with filigree, 3D printed parts and computer aided designs and simulation can be used measure the (sub)milli-Newton range. The latter requires careful design and manufacture as well as assembly and calibration, and tested, which is trialled here on a specimen of a meat ant (*Iridomyrmex purpureus*) validating the design of Sepehrirahnama et al (2023) but in a modular arena and synchronised with close-up video capture in two perspectives.

2. Design process

4.1 Miniature-force plate

We use an HP MultiJet powder-based 3D printer for the manufacturing of a miniature force plate, capable of printing small, intricate components without the use of supports, therefore providing an advantage over resin-based prints (Ngo et al., 2018). Powder based printing, a form of additive manufacturing, has drawn interest in various fields due to its "unlimited design freedom, optimization, lightweight and customization" (Alarifi 2024). The HP Printer available at UTS Tech Lab uses PA-12, a polymeric powder which shares (once set) similar mechanical properties to Formlabs SLA resin, a previously proposed material for MFP prints (Sepehrirahnama et al, 2023).

Table 1 – Key Material Properties of PA-12 compared to Formlabs Resin

Parameter	Formlabs Resin	PA-12 Polymer
Young's modulus, E (GPa)	1.6-1.8	1.25
Density, r (g/cm^3)	1.1-1.2	1.01
Poisson's ratio, v	0.35	0.33

Two prints of the MFP were completed: the first featuring a 4x4 mm^2 force plate, and a second covering an area of 2x2 mm^2. The print of the 2x2 mm^2 tread plate warped slightly during printing while the 4x4 mm^2 sized one was largely stable and presented an acceptable balance of rigidity, flexibility, and structural integrity. The rough surface would allow for the strain gauges to be attached without sanding the structure, removing a step which could cause damage via human error. Furthermore, printing the MFP without supports reduces the risk of damage during support removal, which could impede experiment progress due to the need of reprints.

4.2 Strain Gauges

The strain gauges utilized for this setup were FLK-1-11 strain gauges from Tokyo Sokki Kenkyujo Co. The FLK series features a narrower gauge width than standard gauges, enabling their placement on the force plate's narrow beam. These strain gauges facilitated data collection at sampling rates of 50 kHz at 100 kS/s (FLK-1-11

50000×10-6 strain, strain limit) and were integrated into the MFP by two configurations. The strain gauges on the uppermost beam were arranged in a half-bridge 2

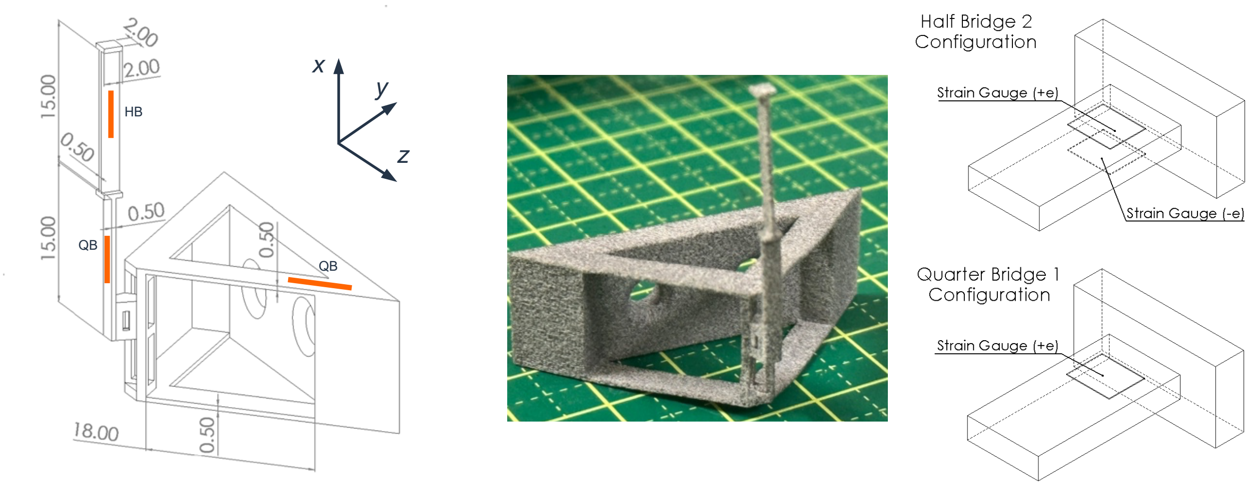

Figure 1 – (a) Labelled 3D Model of miniature force plate (MFP) with beam thicknesses (units [mm]); orange line indicates strain gauge location (HB-half bridge 2, QB- quarter bridge 1) and (b) PA12 printed model, design adopted from (Sepehrirahnama et al., 2023) (c.1) Diagram of Half-Bridge 2 Configuration (c.2) Diagram of Quarter-Bridge 1 Configuration.

configuration to measure bending force in the *x*-direction. The half-bridge 2 configuration utilizes two active strain gauges mounted on the top and bottom side of the strain specimen, seen in Figure 1 (c.1). By contrast, the strain gauges measuring the *y*- and *z*- force components were in a quarter-bridge 1 configuration, presented in Figure 1 (c.2), using a single strain gauge and a quarter bridge completion resistor connected to the NI-DAQ module 9237. Due to the short impact time of the feet (gait cycle of lowering and lifting the feet in a tripod configuration ca 34 ms, with subprocesses having lengths of only about 0.4 ms (Oberst et al. 2015)), at least 10 times faster response times are required to measure accurately the changes in strain (ie ca 40 μs at least). The NI-9237 can measure down to 20 μs.

To attach the strain gauges, the following protocol was followed: Firstly, the surfaces were cleaned using methylated spirit on a cotton bud. Strain gauges were removed from their backing and placed on non-stick paper. Cellophane was placed on the other side of the strain gauge, and delicate force was applied to ensure it adhered evenly. Next, the non-stick paper was carefully peeled off without curling the strain gauge. Glue was applied to the surface of the force plate beam, and the exposed surface of the strain gauge was placed on the beam, using light force on the cellophane to secure it in place. Finally, the edges of the cellophane were trimmed.

4.3 Video Capture

When recording at high framerates, the 50 Hz AC flickering of the ceiling lighting can become problematic (Oberst et al., 2014, Li et al., 2016). Cameras operating at several hundreds of frames per second capture dark frames caused by the bulbs and will appear as flickering within the recording. This can be remedied by using DC power light sources, such as flashlights or LEDs. Another issue of high framerate recordings is the necessity to use low light exposure settings or very high light intensity, as each frame has less time to capture to capture an image. Hence to achieve excellent results, lower light exposure settings in a camera require significantly more lighting than regular image capture. To address these challenges, we opted to maintain a low light exposure setting on the camera while increasing the overall light intensity using a white light box with LED strip.

A critical issue in our experimental setup was the synchronization of camera recordings with strain gauge measurements. Due to the complexities of timecoding and synchronisation, video capture was substituted for highspeed image capture. Via the cameras native software development kit (SDK), we were able to capture approximately 120 frames per to rise, thereby aligning the timelines of camera, strain and force data capture.

4.4 Arena Design

The newly designed arena incorporates several key features to enhance its functionality and adaptability (Figure 2). It features a detachable top and bottom design, facilitating ease of assembly and disassembly for maintenance and experimentation purposes. This modular design allows rather ad-hoc modifications or replacements as needed, streamlining the experimental process, and minimizing downtime. Vertical slots are integrated into the arena to accommodate the MFP, enabling adjustable positioning to suit different experimental setups and requirements. This versatility ensures that the MFP can be precisely positioned to capture relevant data while accommodating variations in experimental design or specimen size. Additionally, the arena includes a removable floor, allowing researchers to experiment with various floor materials or MFP configurations. This feature enables the customization of experimental conditions to suit specific research objectives, providing flexibility in experimental design and data collection.

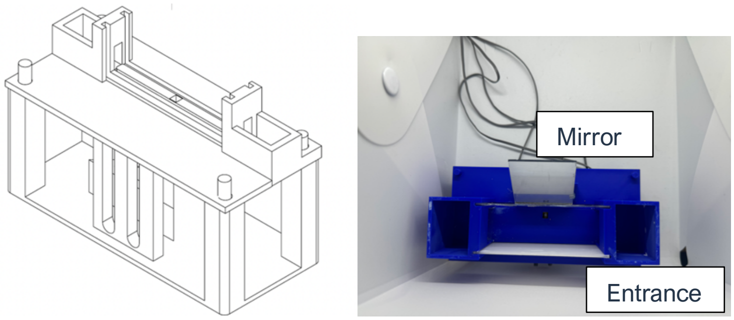

Figure 2 –(a) Drawing of 3D Model of Insect Arena Setup and (b) 3D Printed Arena with Perspex Sheets and Mirror Affixed

A narrow corridor within the arena ensures that insects interact with the miniature force plate during locomotion, optimizing data collection by constraining the insect so increasing the possibility to establish contact with the sensing surface. This design choice minimizes experimental variability and enhances data accuracy, facilitating robust analysis and interpretation of arthropod behaviour. The arena also incorporates supported external chambers for housing insects before and after experiments, providing a controlled environment for observation and manipulation e.g. as required to run bioassays choice experiments over several days. Two one-millimetre slots are included in the design, allowing for the adjustment of the amount of light entering the arena to suit experimental conditions (in our case via coloured and clear Perspex). Finally, space is allocated on the upper floor of the arena to affix different mirror angles, offering flexibility in capturing side views of insects and accommodating varied experimental setups and perspectives. This design element enhances the versatility of the arena, enabling customized image configurations to meet the specific requirements of their experiments.

5 VALIDATION

4.1 Miniature-force Plate Calibration

The miniature force plate calibration was conducted on an optical table ensuring isolation from external vibrations. The miniature force plate was securely mounted using screws and washers to the 3D printed arena base. For each directional force, the miniature force plate was rotated so the Modal Hammer (DJB IH-01 Modal Hammer / piezoelectric IEPE force sensor) could excite the tread plate in the respective direction. During *z*-axis testing, the modal hammer struck the centre of the tread plate, whereas for *x* and *y*-axis testing, the modal hammer impacted the tread plate along its respective edges (Figure 3). Force data was collected through

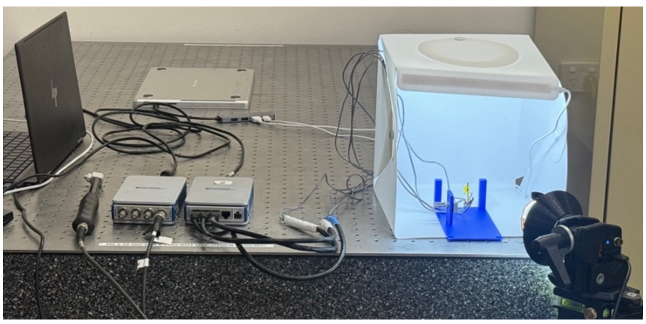

Figure 3 – Experimental Setup of MFP Calibration featuring the NI-DAQ Modules and the

the piezoelectric IEPE force sensor in the hammer connected to an NI-DAQ Module via BNC cable. Microstrain data was gathered via an additional NI-DAQ module (NI-DAQ module 9237, 4 differential input channels, 50 kS/s sample rate, 24-bit resolution, ±25 mV/V input range). Data recording and file saving were managed using LabVIEW Version 2024 Q1 Suite+, while high-speed camera images (Mars640-815/uc) were simultaneously captured with the native camera software iCentral (Figure 3).

4.2 Arthropod Locomotion Testing

Iridomyrmex purpureus, commonly known as meat ants, were collected from Voyager Point Wetlands (33°57'22.5"S 150°58'27.5"E) and stored in containers with tissue papers soaked in water-diluted honey. The ants were then transferred to the Bioacoustics Lab at UTS Tech Lab and kept in Thermoline environmental cabinets (CLIMATRON-520-DL) set at 28℃ and 60% relative humidity until needed for experiments. The ants (with documented average weight of about ca 27 mg and an average length of 14 mm, cf. Oberst et al., 2017) therefore being about twice as long compared to *Formica polyctena* used by Reinhardt and Blickhan (2009). While much larger than the specimens we intend to use eventually for the finalised version of the force plate, these ants deemed suitable for initial testing.

On the day of insect testing 20 mm from the surface top layer, fluon was applied to the upper walls of the arena and allowed to dry, to prevent insects from climbing out. During testing, the insect arena with an affixed mirror and attached miniature force plate was placed in the lighting box, and a camera was positioned above using a tripod. Lights on the 3D-printed lens and lighting box were turned on to illuminate the arena, and insects were introduced through the side entrance using forceps (Figure 4). Recordings were taken in 1-minute intervals at a frequency of 1,200 Hz, applying a first order Butterworth Filter at 150 Hz.

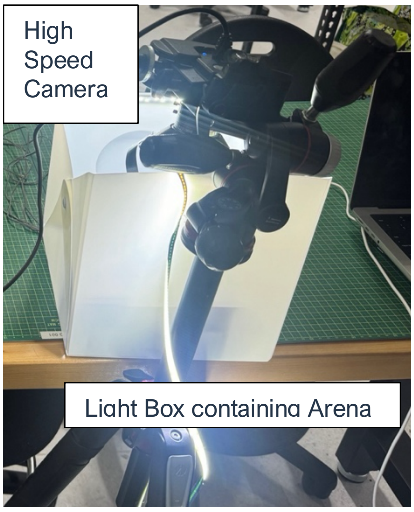

Figure 4 – Insect Locomotion Experimental Setup

5 RESULTS

4.1 Calibration Results

The curve for the *x* axis excitation in Figure 5 features a lower slope (13.28) compared to the *y* (87.82) and *z* (141.29) directions. The increased sensitivity of the *x*-axis measurements may be attributed to its Half Bridge 2 strain gauge configuration, enabling it to measure smaller changes in electrical resistance in contrast to the quarter bridge configurations. Furthermore, the impact of wires on the force plate adding weight could potentially skew the measurements. Images from the *y* axis excitation calibration test shows that the vertical beam had a bend over time which could have impacted readings.

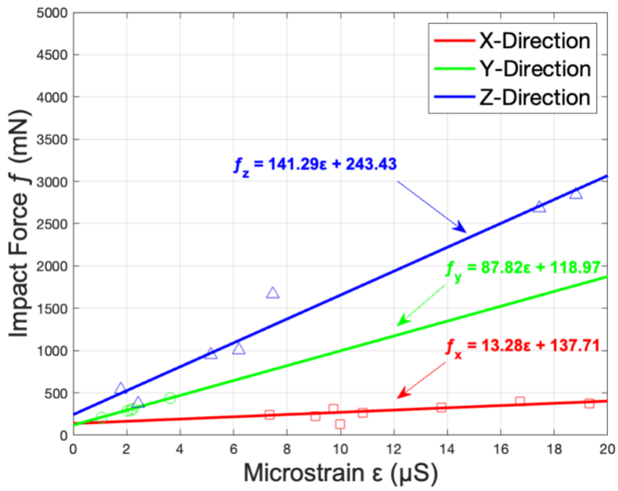

Figure 5 – Plot displaying the Strain-Force Relationship for Triaxial forces on the PA12 MFP

The curves created from the relationship between microstrain, and force could be greatly improved with a larger sample size. More samples over a larger force range, like that of Sepehrirahnama et al. (2023), and removing outliers, would create a more reliable and valid curve. Furthermore, using a manual hammer presented issues of double hitting, and sliding against the surface of the force plate. Also, it is more difficult to control the magnitude of force on a manual hammer as opposed to an automatic impact hammer, as used in Sepehrirahnama et al. (2023). Preferential to both is miniature force plate excitation via a ball bearing as used in (Reinhardt et al., 2014b), which necessitates high speed video and data synchronisation, unlike the former methods.

4.2 Image Capture of Impact Force

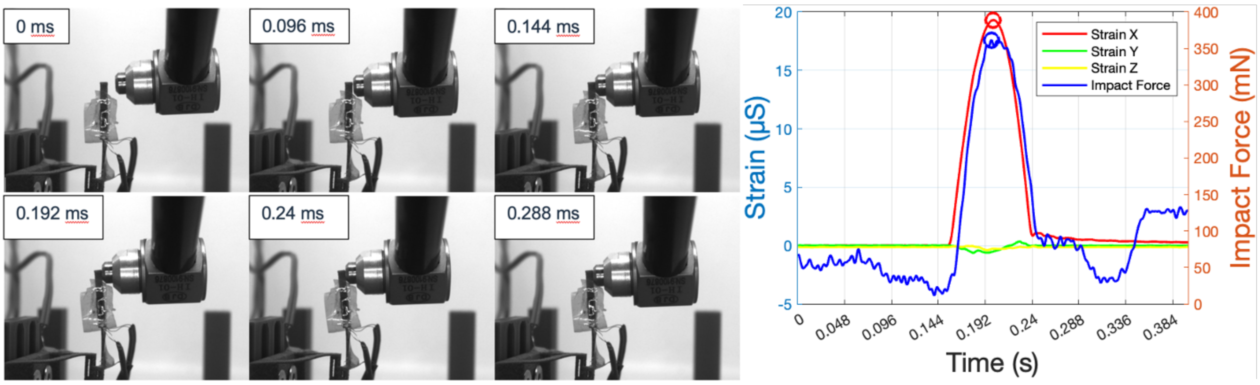

Figure 6 – left: timed image capture of x-axis excitation; right: plot displaying the force and strain measurements of a single excitation of the x-, y- and z- directions during calibration.

Figure 6.a shows the synchronised recording of the force data from the impact hammer and strain data from each of the 3 strain gauge configurations during an excitation of the system in the *x*-direction. Overall, a good match between the strain data and the impact force data could be obtained. Our experimental setup enabled us to enact the procedure used in (Reinhardt et al., 2014) to accurately calibrate future miniature force plate prints.

4.3 Insect Locomotion Test

The insect arena was successful in capturing images from both a top down and side-view of insect anatomical structure during locomotion and include a view on the MFP (Figure 7). Using the available hardware, approximate 140 images were captured per second via the native camera SDK. This figure would drop to 115-120 images when simultaneously collecting strain gauge and force data via LabVIEW. The 140-image figure could be increased via using an alternative device to collect strain gauge data or implementing hardware with more powerful processing speeds.

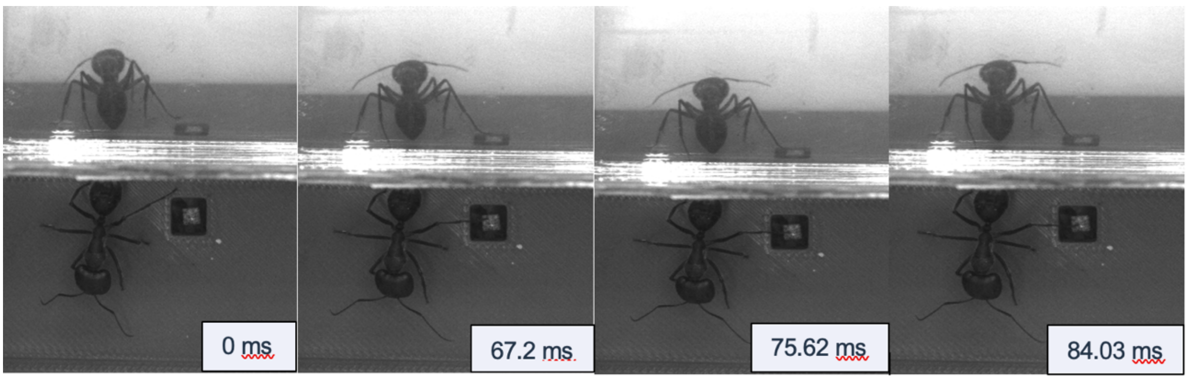

Figure 7 – Image Capture of ant (Iridomyrmex purpureus) interacting with PA12 MFP

5 CONCLUSION

Arthropod locomotion on the miniature-force plate could not be observed via the collected strain gauge data. Signal noise was significant and could be reduced by conducting the experiment within an anechoic chamber to isolate the system from external frequencies. Implementing Half-Bridge or Full-Bridge configurations, especially in the *z*- axis would increase the sensitivity of the miniature force plate. As proposed by Sepehrirahnama et al. (2023) further reduction in beam width to 0.2 mm may also increase the plate's ability to pick up forces in the sub-millinewton range. Combining these suggestions with the additive manufacturing technique of powder printing may provide the sensitivity needed to measure the triaxial forces of insect locomotion.

The modular design allows for the rapid production of arenas for the purposes of insect bioassays. Furthermore, calibration data from the miniature force plate display the potential of additive manufacturing techniques in the printing of miniature-force plates. By implementing the improvements suggested in Sepehrirahnama et al. (2023), our setup has the potential of measuring forces in the sub-millinewton range, as required for the measurement of ant locomotion.

The measurement of forces in the μN range, however, while theoretically possible (Sepehrirahnama et al. 2023) still requires verification. For the validation of sensitivity, the existing setup could be compared to the resin print of Sepehrirahnama et al. (2023); a further step in increasing quality of the miniature force plate could be the use of nilon prints. These validation measurements as well as the synchronization of image and strain data on insects though needs to be tested using an anechoic environment. The use of a half-bridge II configurations everywhere would increase sensitivity, but it would also increase cross-coupling effects which we did not observe extensively in our experiment. This cross-talk will need to be quantified in the next round of measurements conducted in an anechoic room. Synchronisation and the use of half-bridges may also require implementing a more precise calibration technique of the MFP, such as nonlinear least squares making eg use of the out-of-diagonal terms of the sensitivity matrix (Reinhardt and Blickhan, 2014b; Sepehrirahnama et al. 2023). However, using two more sensors also bear the risk of having interference effects, e.g. in the Half Bridge 2, which is known to be an issue due to unintended strain and/or thermal effects and should be also carefully evaluated with an improved calibration process.

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REFERENCES

Alarifi, I. M. (2024). Revolutionising fabrication advances and applications of 3D printing with composite materials: a review. *Virtual and Physical Prototyping*, *19*(1). https://doi.org/10.1080/17452759.2024.2390504

Adam, G., Boudaoud, M., Reynaud, V., Agnus, J., Cappelleri, D. J., & Clévy, C. (2024). An Overview of Microrobotic Systems for Microforce Sensing. *Annual Review of Control, Robotics, and Autonomous Systems*, *7*(Volume 7, 2024), 359–383. https://doi.org/10.1146/annurev-control-090623-115925

Fattoruso, V., Sepehrirahnama, S., Tofigh, F., Lai, J., Nowotny, M., & Oberst, S. (2022, July). *Consideration on how to improve ground reaction force measurements in small walking insects*. 28th International Congress on Sound and Vibration, Singapore.

Hernandez, A. M., Schiebel, P. E., Shum, J., & Wood, R. J. (2024). Spines and Inclines: Bioinspired Spines on an Insect-Scale Robot Facilitate Locomotion on Rough and Inclined Terrain. *Integrative and Comparative Biology*, icae145. https://doi.org/10.1093/icb/icae145

Robotics (pp. 433–440). WORLD SCIENTIFIC. https://doi.org/10.1142/9789814415958_0056

Li, S., Tan, S.-C., Lee, C. K., Waffenschmidt, E., Hui, S. Y., & Tse, C. K. (2016). A survey, classification, and critical review of light-emitting diode drivers. IEEE Transactions on Power Electronics, 31(2), 1503–1516. DOI: 10.1109/TPEL.2015.2417563

Li, C., Zhang, T., & Goldman, D. I. (2012). A resistive force model for legged locomotion on granular media. In *Adaptive Mobile*

Montagut Marques, M. J., Yuxuan, Q., Sato, H., & Umezu, S. (2024). Cyborg insect repeatable self-righting locomotion assistance using bio-inspired 3D printed artificial limb. *Npj Robotics*, *2*(1), 1–14. https://doi.org/10.1038/s44182-024-00009-w

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

Oberst S, Nava-Baro E, Lai JCS, Evans TA, “Quantifying ants’ activity using vibration measurements”, PLoS ONE, 9(3): 90902.

Oberst, S., Nava-Baro, E., Lai, J.C.S., & Evans, T.A. (2015) An Innovative Signal Processing Method to Extract Ants’ Walking Signals, Australian Acoustical Society, 43(60), (87-96). DOI: 10.1007/s40857-015-0003-x

Oberst, S., Blann, G., Lai, J. C. S., & Evans, T.A. (2017) Cryptic termites avoid predatory ants by eavesdropping on vibrational cues from their footsteps. Ecology Letters, 20, 212-221. DOI: 10.1111/ele.12727

Ortega-Jimenez, V. M., Jusufi, A., Brown, C. E., Zeng, Y., Kumar, S., Siddall, R., Kim, B., Challita, E. J., Pavlik, Z., Priess, M., Umhofer, T., Koh, J.-S., Socha, J. J., Dudley, R., & Bhamla, M. S. (2023). Air-to-land transitions: From wingless animals and plant seeds to shuttlecocks and bio-inspired robots. *Bioinspiration & Biomimetics*, *18*(5), 051001. https://doi.org/10.1088/1748-3190/acdb1c

Reinhardt, L., Weihmann, T., Blickhan R. (2009) Dynamics and kinematics of ant locomotion: do wood ants climb on level surfaces? J Exp Biol, 212 (15), 2426–2435. DOI: 10.1242/jeb.026880

Reinhardt, L., & Blickhan, R. (2014). Level locomotion in wood ants: Evidence for grounded running. *Journal of Experimental Biology*, *217*(13), 2358–2370. https://doi.org/10.1242/jeb.098426

Reinhardt, L. & Blickhan, R. (2014b) Ultra-miniature force plate for measuring triaxial forces in the micronewton range. Journal of Experimental Biology, 217, 704-710. DOI: 10.1242/jeb.094177

Rizwan ul Haq, M., Nazir, A., Lin, S.-C., & Jeng, J.-Y. (2022). Design and performance evaluation of multifunctional midsole using functionally gradient wave springs produced using MultiJet fusion additive manufacturing process. Materials Today Communications, 31, 103505. DOI: 10.1016/j.mtcomm.2022.103505

Sepehrirahnama, S., Sansom, T., Lai, J. C. S., & Oberst, S. (2023). Investigation of vibration response of a miniaturised micro-force plate for the study of termite’s locomotion gaits. In Proceedings of the 29th International Congress on Sound and Vibration. Prague: International Institute of Acoustics and Vibrations. Available at http://hdl.handle.net/10453/171579

Shimazaki, K., Sugimoto, T., Toda, H., & Takahashi, H. (2022). A Polyimide Film-Based Simple Force Plate for Measuring the Body Mass of Tiny Insects. *Sensors*, *22*(21), Article 21. https://doi.org/10.3390/s22218352

Sugimoto, T., Kawasaki, Y., & Toda, H. (2022) Measurement method of a microspring-supported force plate with an external laser displacement meter. Measurement science & technology, 33(10), 105-118. DOI: 10.1088/1361-6501/ac7b12

Takahashi, H. MEMS-Based Micro Sensors for Measuring the Tiny Forces Acting on Insects. Sensors, 22, 8018. (2022) DOI: 10.3390/s22208018

Werfel, J., Petersen, K., & Nagpal, R. (2014). Designing Collective Behavior in a Termite-Inspired Robot Construction Team. *Science*, *343*(6172), 754–758. https://doi.org/10.1126/science.1245842

Wu, Y., Yim, J. K., Liang, J., Shao, Z., Qi, M., Zhong, J., Luo, Z., Yan, X., Zhang, M., & Lin, L. (2019). Insect-scale fast moving and ultra-robust soft robot. *Science Robotics, 4*(32), eaax1594. DOI: 10.1126/scirobotics.aax1594

Xuan, Q., & Li, C. (2023). Environmental force sensing helps robots traverse cluttered large obstacles. *Bioinspiration & Biomimetics*, *19*(1), 016002. https://doi.org/10.1088/1748-3190/ad0aa7