Authors’ response (Reviewers’ comments in blue)

We sincerely thank all the reviewers for the thorough and extremely useful reviews as well as the positive comments.

Reviewer 1

The manuscript by Maniatis et al. is greatly improved from the first version. I mostly have minor suggestions to clarify various points, including how the authors describe and define entrainment. I recommend publication after minor revisions.

Thank you very much for your time and effort.

7-8: “This paper introduces and tests a theoretical framework that connects the IMU measurements with the forces applied on a sediment grain moving on a riverbed”. To me this sentence still implies that the authors independently “test” their calculations of forces, which they do not. Suggest saying something like they develop a theoretical framework for calculating drag and lift forces on grains that are in motion, based on IMU measurements.
Replaced with:

“This paper develops a theoretical framework for calculating drag and lift forces on grains based on IMU measurements”.

42: remove “and”

Done

58: remove comma after Gimbert et al citation.

Done

116: suggest changing to “… record zero acceleration (and therefore zero net force) until…”
Done

118: Could cite Garcia et al (2007) here for grain vibrations prior to entrainment.

Garcia, C., H. Cohen, I. Reid, A. Rovira, X. U´beda, and J. B. Laronne (2007), Processes of initiation of motion leading to bedload transport in gravel-bed rivers, Geophys. Res. Lett., 34, L06403, doi:10.1029/2006GL028865.

We thank the reviewer for the excellent suggestion, inserted.

142: remove comma after “equations 1 and 2”. Next line, change e.g to e.g.

Done

169: suggest changing “completely immobile” to “not moving”.

Done

Equation 12: An equation without a relationship operator just feels wrong to me. Add a variable for impulse and an equals sign.

That was a typo, corrected.

223: YEI capitalized, but not capitalized in line 232, be consistent.

Corrected

267-269: The definition of “entrainment point” is unclear. To me, “the initiation of the vibration that dislodges the particle by one particle diameter” unambiguously says that entrainment is defined as the moment the particle very first starts vibrating, if later on it moves by one particle diameter before stopping to vibrate. But I don’t think that is what the authors actually mean, because Figure 3 shows “dislodgement” well after the initiation of vibrations, and line 285 says that there were pre- and post-entrainment vibrations (the actual definition given would mean zero vibrations before entrainment).

I am not sure, but my guess is that the authors actually define entrainment as the time when the particle has moved by one particle diameter, as implied in lines 281 and 284. If the time of entrainment is measured entirely by video, say this in the paragraph starting at line 267, because otherwise it is not clear how you know when the particle has dislodged by one b-axis. I also would remove “independently” from line 281, because it implies that entrainment was also measured in some other way, but I don’t think this is true. I think entrainment time was measured from the video, and then the forces and impulses before and after this time were calculated from the IMU data.

The reviewer’s observations are correct
For clarification we replaced the text in lines 266-267 with:
Line 267: ‘We define entrainment as when the particle moves by one particle diameter, or b-axis length for the ellipsoid. Having identified the time when the grain has moved by this distance from the video, the timing of the vibrations which directly and continuously preceded entrainment was also determined from the video. Many periods of vibration which do not lead to entrainment were recorded by the sensor and are visible on the videos.’

Figure 3 instead uses the term dislodgement. Is this different from entrainment? Be consistent, if dislodgement is the same then use the same term; if different then define dislodgement.

Changed to Entrainment

The authors should also expand on why they define the threshold of motion as the probability of entrainment > 0.5.

Line 323 Text added:
The threshold probability of 0.5 corresponds to the impulse at which the probability changes from the particle being more likely to be at rest, to being more likely to be entrained. In this context, with this approximation we calculate a gradational threshold of entrainment (Begin and Schumm, 1979) and not an absolute one.

Figure 2 caption, last line: remove “which”.
Done

309: give equation numbers for drag and lift forces.
Done

315: After reading the manuscript, I have a slightly better but still incomplete understanding of why the authors say that the ellipsoid sensor demonstrates a strong influence of lift forces. The issue is that lift forces are smaller, so it seems like they should be less important. And they’re also less well correlated for I vs t. When I first read this I was just confused. I suppose lines 325-327 are the explanation. Maybe the point that I’m missing that the data presented only reflect timeseries that did lead to entrainment? Also, did the authors test whether drag and lift time series are correlated in their actual data? The figure 7 analysis assumes they are independent, but its not clear that they are independent in the actual data. Apologies if it is in the manuscript and I missed it.

Response

It is not possible to do this comparison for the actual data (point forces), because impulses need to be defined for specific time frames. In this presentation this is the time frame where the sensor was recording net forces > 0. During those periods (over the threshold of motion) the lift forces are can be smaller in magnitude, but they are also much more frequent. This is the observation on which we base our interpretation of the influence of the lift forces on the ellipsoid.

To clarify further to the above, we added the following sentence it the captions of Figure 4 and 6. “Impulses of all the inertial forces that exceeded the gravity forces”, to clarify further that the values correspond to over 0 net force impulses.

In addition, the drag and lift forces are uncorrelated as indicated in Appendix E. This gives us some confidence for the calculation presented in Figure 5, showing that the lift threshold is lower than the drag for the ellipsoid, supporting further the control of lift impulses. To highlight this more we added a sentence in lines 452-454 which now read as

“After the normalisation, the laboratory and field results are combined into one dataset of normalised drag (I_{Drag}) and normalised lift (I_{Lift}) impulses, which are assumed to be uncorrelated. The latter is justified by the fact that the point lift and drag forces are statistically uncorrected as shown in Appendix E (Figure E2”

Figure 4a: seems like the y axis should be expanded to show the data over more than 10% of the plot area.

Figure 4a shows all the periods that net force is> 0

387: runon sentence, particles not articles. Change to “…diameter particles. The measured…”

Done

390: there is a bonus "s".
Corrected

392: expand just a bit on fully developed flows. I think you mean something like "…flows much deeper than the particle diameters, with fully developed boundary layers."
Done

413: Are the numbers flipped?
Corrected.

416: I presume instantenuous is another physics term I'm unfamiliar with? Trying to understand the physics in this paper, I sometimes have an immediate feeling of "huh?" … instantenuous. But seriously, this is my favorite new word portmanteau. And I really do like and appreciate the manuscript!

That was a typo, we mean instantaneous. We really appreciate the positive comments!

432-435: break into two sentences.

Done

Reviewer 3

The authors have done an excellent job responding to the questions and updating the manuscript. The changes made are all in the right direction, and I think that the paper can be published with only minor revisions. My remaining comments are given below.

Thank you very much for your time and effort.

(1) With respect to the flume setup, around L255 and follows makes me think that water can flow under the ellipsoid particle whereas water did not really flow under the sphere. If water could indeed flow under the ellipsoid particle, then I expect this had something to do with the dominance of lift. Please be clear about the exact way in which the two test particles sat in the flume with respect to the surrounding sediment.

Response:
The sphere and the ellipsoid were at comparable elevations in the bed because the gaps between the hemispheres were covered by the sand coating as we explain in the text (255-257) The protrusion of ellipsoid is approximately equal to its c-axis. (0.03, D1) as it is fully supported by the hemispheres. This makes the protrusion of the ellipsoid smaller than the one of the sphere. Despite the ellipsoid being at full contact with the hemispheres, there is a possibility that a film of water could flow between the coating/ gap filling gravel and the particle. Because, we observe the same control of the lift force in the field experiment (where the ellipsoid was placed on bare bedrock) we think that ,for this degree of protrusion, this film of water wouldn't have a very strong effect. However, we cannot quantify that, and we added a comment in the legend of Figure 2 so the readers are aware of this issue.

“While the spherical particle was in full contact with the bed (hemispheres and coating/filling gravel), the setting could result to a film of water flowing underneath the ellipsoid. “

(2) Along with comment 1, please include the approximate height of the ellipsoid particle in Fig 2 as you have done for the sphere.

Added: Line 257

(3) Are the critical depths in Fig 2 measured or estimated based on Shields? If they are estimated based on Shields, please put the actual measured depths in Fig 2 rather than the calculated critical depths.

The depths are measured at the point of entrainment and all the hydraulics are calculated for the same conditions. This is now clarified in Figure 2 and table D1. We also replaced critical depth with measured depth in lines 275-277.

(4) I expect that the relative importance of lift vs drag on a particle has as much to do with how the particle sits in the bed then it does with particle shape. Wouldn't you expect that lift is more important in mobilizing a sphere if the top of the particle of interest is down near the top of the surrounding bed particles rather than being perched and exposed up on the bed top? Could you argue that the importance of lift for the ellipsoid has to do with protrusion as much as it does particle shape? If so, please discuss, or at least comment on protrusion and its link to your test particles and outcomes.

We have now clarified that the sphere and the ellipsoid are in comparable elevations in the bed. We completely agree that the lift forces will exert a much higher control for lower protrusion values, but our settings (in both the flume laboratory and the field) correspond to highly exposed to the flow particles. In this context, we added a comment in the discussion:

Line 379:

“In addition, it is useful to note that grain protrusion is not discussed in this work, despite being an important control on grain motion and particularly entrainment (e.g. Dey and Ali, 2018), since the presented laboratory and field experiments only correspond to particles that are highly exposed to the turbulent flow.”

Reviewer 2

I served as one of the reviewers of this manuscript at its first submission. The authors has considered my suggestions seriously and applied them to this revision. After major improvements has been made, I think this manuscript is ready for publication in the Earth Surface Dynamics.

Thank you very much for your time and effort.