Incorporating Six Pre-Defined Experiments Using Motion Analysis into Engineering Dynamics Courses

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Introduction

Undergraduate engineering dynamics courses often lack a concrete connection between methods learned and hands-on engineering applications. This course is required for a variety of majors from mechanical and aerospace engineers to architectural and biomedical engineers. However, dynamics is a dreaded course for many students due to the difficulty of material, transitional stage of their college career, and the relevance of the subject to their major[1]. Another issue that has been observed is that the experiences taught in undergraduate dynamics are not genuine[2]. A typical lecture course may not focus on the extension of in-class theories, examples, and idealizations to physical dynamic systems.

To combat these issues, many authors have discussed the benefits of active, project-based learning over traditional, passive lecture courses[3]. We tried to create a stronger link between real life problems and theory using motion capture technology. In a previous study, we used motion capture technology to let dynamics students create their own experiments to analyze[4]. However, students struggled to create a streamlined, multistep analysis when designing their own experiment from scratch. We wanted to create a more defined approach so students could experience dynamic data and experiments without having to create the entire process themselves. Thus, this paper focuses on the use of six pre-defined experiments which introduce students to motion capture technology to analyze the kinematics and kinetics of real-life situations.

This study uses the motion capture technology available at the Human Motion Biomechanics Lab (HMBL) at California Polytechnic State University (Cal Poly). Motion capture technology is used in a variety of industries from clinical biomechanics to computer animation[5,6,7]. Although a three-dimensional motion capture laboratory was used for this study, new two-dimensional motion study apps (such as Video Physics, Playground Physics, and Tracker) for smart phones allows experiments like those presented in this paper to be analyzed in almost any classroom.

The objectives of this study were to (1) introduce students to analyzing sets of data which show students that experimental data does not always match theory, (2) expose students to dynamic variables that change with time, (3) connect fundamentals learned in class to real-life situations, (4) show students the variance in theoretical and experimental data, and (5) provide a structured assignment to compare the outcomes of pre-defined experiments with students creating their own experiments for future work.

Consequently, the student learning objectives for the assignments were to (1) interpret real data, (2) plot and analyze dynamic variables over time, (3) apply fundamentals of dynamics correctly to the data, and (4) analyze experimental errors through both computation and thoughtful predicted sources of error.

Methods

Six different experiments were created in the Human Motion Biomechanics Laboratory (HMBL) for dynamics students to run and analyze. The HMBL includes a motion capture system that consists of near infrared cameras which track the location of retroreflective markers using the

video processing software, Cortex. The HMBL also has four force plates for kinetic data collection of ground reaction forces.

Experiments were created to analyze a bicycle, an elliptical exercise machine, a student's gait, a student rowing, a trebuchet catapult and a Geneva mechanism. The HMBL team which created these experiments consisted of four undergraduate and one graduate mechanical engineering students under the supervision of a mechanical engineering professor. The HMBL team identified dynamics variables to be solved for each experiment. The full project description, including marker placement location on the equipment, for each experiment can be found in Appendix A. Students were provided with position data throughout the motion, and then were taught to numerically differentiate the data to find velocities and accelerations. The project, dynamic principle, and requested deliverables are shown in Table 1.

Table 1. Six experiments and their corresponding dynamics principles to be tested and requested deliverable from students.

Project	Dynamic Principle	Requested Deliverable
Bicycle	Rigid body kinematics	Compare experimental and calculated values, plot dynamic variables as a function of time
Elliptical Exercise Machine	Rigid body kinematics	Compare experimental and calculated values, plot dynamic variables as a function of time
Gait	Rigid body kinematics, rigid body kinetics	Compare experimental and calculated values, plot dynamic variables as a function of time
Rowing	Rigid body kinematics	Compare experimental and calculated values, plot dynamic variables as a function of time
Trebuchet Catapult	Rigid body kinematics, rigid body work-energy	Compare experimental and calculated values
Geneva Mechanism	Rigid body kinematics, polar coordinates	Compare experimental and calculated values, plot dynamic variables as a function of time

The HMBL team pre-collected data for each experiment before students were brought into the HMBL, shown in Figure 1, to ensure consistency in results among teams. The relevant data for each experiment was prepared in a spreadsheet for the students. An example section of the kinematic and kinetic output for the gait experiment can be found in Appendix B. A derivative calculator spreadsheet, which used first and second order finite difference method differentiation, was created for the students to find velocities and accelerations from the positional data.

Figure 1. Panoramic image of the Cal Poly Human Motion Biomechanics Laboratory.

Over the course of a week, sixty-six dynamics students with majors ranging from mechanical, civil, aerospace, biomedical and architectural engineering were introduced to the HMBL at Cal Poly for the project. They chose which experiment they wanted to do for their project by signing up for a 30-minute time slot specific to an experiment. Students arranged themselves into groups of three. There were three or four groups for each different experiment.

We gave students a tour of the lab and described how the infrared cameras record the retroreflective markers' positions. Students were then guided through the marker placement for their experiment. The students took positional data for their experiment, but the HMBL team processed it for them. However, after running several trials for their experiment, students were shown how data is processed with the Cortex 7.0 system, if time permitted. The laboratory introduction usually took five minutes, the data collection fifteen minutes, and the last ten minutes were used for data processing and talking to students about research opportunities at the HMBL.

Students were provided with the experimental data, derivative calculator, and the problem statement worksheets (given in Appendix A) a day after all the experiments concluded. They were given a week to write a memo-style report outlining their findings. After turning in the report, the students were asked to select whether they Strongly Agreed, Agreed, were Neutral, Disagreed or Strongly Disagreed with the statements listed in Table 2. Students were also asked about their recommendations for future sections of the course.

Table 2. Survey statements in which students were asked whether they Strongly Agreed, Agreed, were Neutral, Disagreed or Strongly Disagreed.

Question #	Statement
1	Incorporating the HMBL into our assignment was interesting to me.
2	Incorporating the HMBL into our assignment helped me visualize concepts related to my course.
3	Incorporating the HMBL into our assignment helped me learn material in my course.
4	Incorporating the HMBL into our assignment got me interested in research.
5	Incorporating the HMBL into our assignment should be incorporated into future sections of the course.

The students were provided with a grading rubric and an outline for memo-writing before they turned in their report. The student work product was examined along with the surveys to determine the level to which students met the learning objectives. A learning objective (LO) was classified

as highly met if over 90% of reports showed clear achievement of the objective either through numerical or written interpretation. An LO was classified as met at a medium level if 50% to 90% of reports showed clear achievement of the objective through either numerical validation, written analysis, or a combination of both. Lastly, an LO was classified as met at a low level if less than 50% of reports showed a clear achievement of the objective, or if a majority of written student survey responses indicated confusion with the related topic. It is important to note that the students were not made aware of the learning objectives of the exercise.

Results

The results from the survey are provided in Figure 2. Sixty-one percent of the responding students strongly agreed or agreed that the experiment helped them visualize concepts related to their course. Thirty-three percent believed that the project helped them learn material in the course and 47% felt neutral. When asked about how the lab should be incorporated into future sections, 44% said the HMBL should be incorporated into an assignment, 47% believed that students should visit the lab for a demo but not include an assignment. Additionally, 4% said that data should be provided as an assignment, but students shouldn't visit the lab and 5% of students said to not include the lab in future sections.
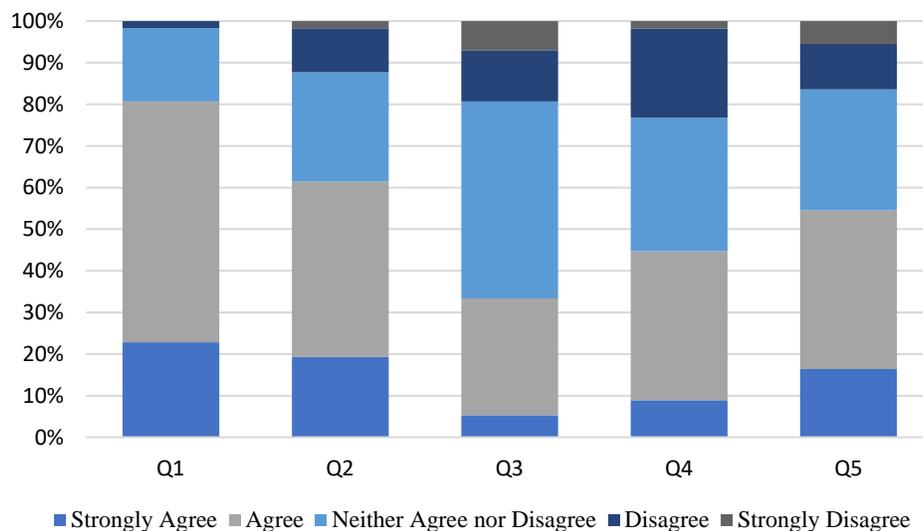

Figure 2. Survey results from the five questions provided in Table 1.

In the survey, students were asked to provide suggestions or comments about the laboratory. A main theme was the irrelevance of the numerical differentiation spreadsheet to an introductory dynamics course. Students had not been taught the technique in the course, and some struggled with incorporating the spreadsheet calculator. Many other students expressed that they were intimidated and unsure how to manipulate a large data set rather than just values at one point in time. Multiple students were frustrated by the lack of an answer key for the open-ended problems.

The Geneva Mechanism was the experiment which was expressed as the most confusing. In this experiment, students took position data of the pin on a Geneva mechanism's drive wheel and corresponding driven wheel. They were asked to use polar coordinate components (r, $\dot{r}$, $\ddot{r}$, θ, $\dot{\theta}$, and $\ddot{\theta}$) to calculate the velocity and acceleration of the pin.

Students struggled to convert their positional data into angular data. They also expressed that the experiment required more knowledge about polar coordinates than was provided in their lecture. Only half of the groups who analyzed the Geneva Mechanism were able to produce accurate graphs and apply the correct equations to their data.

The gait experiment was expressed as the most straight-forward to analyze. In the student's analysis, they were able to apply fundamental methods taught in class such as rigid body kinematics and drawing a Free Body Diagram (FBD) and Kinetic Diagram (KD) to solve for rigid body kinetics. Additionally, they were able to comment on the effects of the assumptions that went into the model, such as treating the motion as two dimensional when it is truly three dimensional.

Other students felt that more hands-on activities like these should be incorporated into dynamics classes. Some students gave suggestions such as providing the Cortex real-time animation to go along with their data, seeing the data being processed, or using the data as an in-class example instead of an assignment.

The level to which the learning objectives were met from the analysis of the student work product are shown in Table 3. Although many students were frustrated with the open-ended nature of the experiment, crucial learning objectives were still met. Students were exposed to the random nature and large volume of real data. They were able to draw conclusions about their experiment using time-based dynamic variables, and they were generally able to correctly compute their theoretical values and compare them with experimental values. Many students noticed how acceleration data can become extremely noisy when differentiating from positional data. Students were able to compare their findings to real-life scenarios to determine if their data made sense, such as the forces present in a person's knee. Most groups gave sound reasoning for errors and abnormal data points. However, some groups gave "human error" as a reason without further explanation.

Table 3. Level of learning objective met from a review of all student reports. (* analyzed for reports containing this deliverable)

Learning Objective	Level Met from Work Product		
	Low	Medium	High
Interpret real data	✓		
Interpret dynamic variables with time*			✓
Apply fundamentals to data		✓	
Propose and analyze experimental errors		✓	

In Table 3, the learning objective of "apply fundamentals to data" is referencing the students' ability to apply the dynamic principles given in Table 1 to their specific experiment.

Discussion

The main learning objective of this laboratory was to expose undergraduate dynamics students to analyzing real-data using the methods they had been taught in class. Some students did not

understand this, as they expressed that they felt the purpose was to get the right answer instead of evaluating an open-ended problem. However, many groups were able to arrive at reasonable conclusions in their reports, fulfilling the main learning objective.

There are some adjustments that could be made to the laboratory for future sections. First, the assignment worksheet should be provided before students come into the laboratory. This will allow students to familiarize themselves with the experiment and allow them to be thinking about how they will analyze the data while they are taking it. Spending more time in the lab to show students how the data is processed may help their understanding of the spreadsheets they receive. Students should also be made aware of the learning objectives before completing the exercise.

Additionally, eliminating the numerical differentiation and instead giving students data in terms of velocities and accelerations may help students interpret the data. Providing students with an example of how to compute values such as angular velocities and segment lengths for all the data within their spreadsheet may help guide students in the right direction. Lastly, improvements to the Geneva mechanism assignment should be made so that it is more clear which variables need to be solved for. This assignment should also be improved to align more closely to the methods taught in the lecture section.

To better understand the effect of this laboratory on student learning, future work is recommended. One option would be to create two similar problems which analyze a course concept utilized in the experiment (such as rigid-body kinematics). The problems could be given to students both before and after they complete the laboratory for signs of improvement in their understanding. A study which spans longer than just one course is also suggested to track students' ability to apply dynamic principles to laboratory-based classes such as Intermediate Dynamics, Controls, and Structural Analysis. A study such as this may provide insight into the effect of students' ability to apply fundamentals to design-based problems through this early-stage introduction to experimental data.

Acknowledgements

References

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Appendix A

Below are the six worksheets outlining the deliverable for each experiment.

ME 212 - Bicycle Experiment

You will be analyzing the motion of various components on a typical bicycle. Using the HMB Lab, we will give you the x-y positions (in mm) of different markers shown in the image above as a function of time. Markers A-B define the rear wheel, markers C-D-E define the bicycle crank, and markers F-G-H-I define the front wheel.

We have provided you with an Excel document that will take the first and second derivatives of these positions. Plot the following as functions of time: the linear velocity and linear acceleration of the bike (you can use marker J), and the angular velocity and angular accelerations of the three rotating segments (Back wheel, front wheel, and crank). You can get these by determining the angle of each segment, and then use the Excel file. These will be your *experimental values*.

Now consider the front wheel at a time when markers F, G, H, and I are as shown in the image above. Using the experimental velocity and acceleration of marker J, the experimental value for angular velocity and acceleration, and the radius of the wheel, calculate the linear velocities and linear accelerations of points F, G, and H along the rim. These are your *calculated values*. Based on your engineering experience, are these values what you would expect to see? Compare these calculated values of the velocities and accelerations of markers F, G, and H to the experiment values at this time.

Now consider the rear wheel and the pedal CE. Compare the angular velocities of the two rotating elements. This gives you a gear ratio; this is related to the cassette (rear gears) and chain ring (front gears). How consistent is this ratio (use Excel to look at the ratio as the wheel rolls)?

ME 212 - Elliptical Experiment
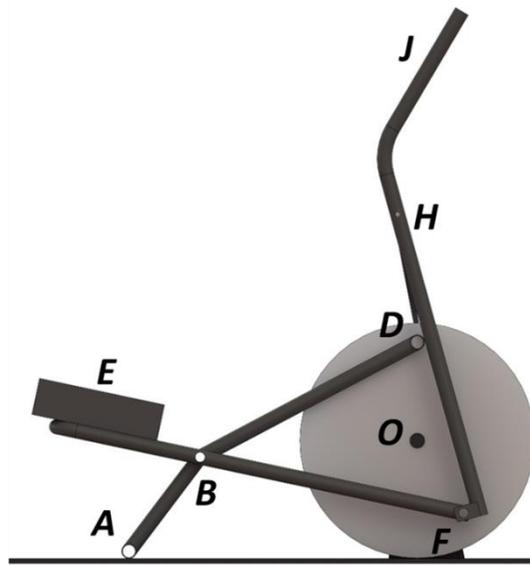
You will be analyzing one of the linkages in an elliptical machine - ODA. Using the HMB Lab, we will give you the x-y positions (in mm) of points D and A as a function of time.

We have provided you with an Excel spreadsheet that will take the first and second derivatives of these positions. Plot the following as functions of time: the velocity and acceleration magnitudes of points D and A, the angular velocities of links OD and AD, and the angular accelerations of links OD and AD. These are your *experimental values*.

Now, choose a time when link OD, the flywheel, is at approximately 45 degrees up from the horizontal. Using the Excel spreadsheet, find the experimental angular velocity and angular acceleration of the flywheel at that time. Given these and the link lengths, calculate the angular velocity of AD and the linear velocity of point A. These are your *calculated values*. Compare these calculated values for ω and v_A to the values you got experimentally.

Now, do the same for the accelerations. Knowing the experimental angular acceleration of the flywheel, calculate the angular acceleration of AD and the linear acceleration of point A. Compare these to the experimental values, and discuss possible sources of error in your analyses.

ME 212 Gait Experiment: Modeling the Lower Leg as a Rigid Body

You will be analyzing the lower leg of a person while walking. Using the HMB Lab, you will be given the x and y position data throughout time (mm), the "Ground Reaction" forces (GRF) in the x and y direction (N) and an Excel sheet that you can use to calculate the first and second derivatives of a data column.
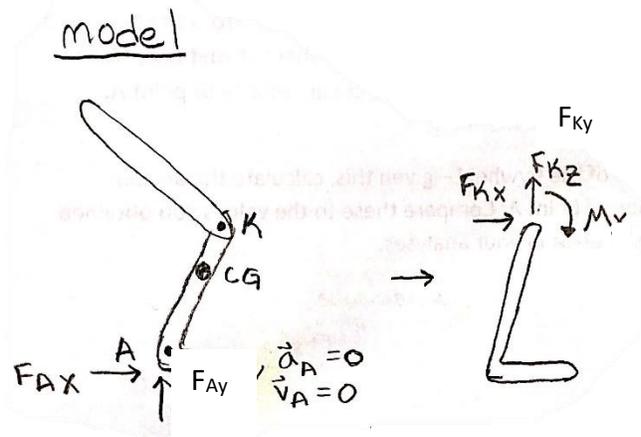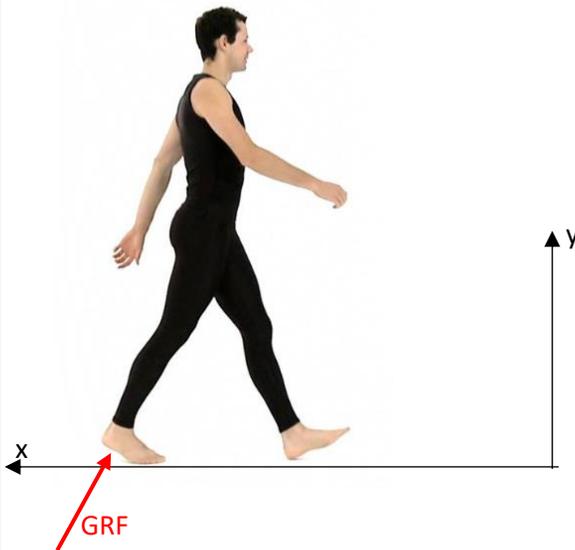
To model the leg as a simplified rigid body, assume the ground reaction forces are acting at the ankle. Treat the foot as a pivot point at this instant of time (i.e., assume point A has zero velocity and zero acceleration). Then, "take apart" the connection at the knee to reveal the internal forces and moment. This is shown in the figure above.

Please do the following:

1. Determine the angle of the lower leg, then use the Excel file we give you to calculate the angular velocity and angular acceleration of the lower leg as a function of time while the walker is on the force plate. Plot both of these as functions of time.
2. Use rigid body kinetics and the relative acceleration equation (you need to find a_G) to determine the reactions at the knee, F_{Kx}, F_{Ky}, and M_k at the instant in time indicated on your data sheet (it will be highlighted for you) if the radius of gyration of the lower leg about its CG is assumed to be .302L, where L is the length of the lower leg. The mass of the lower leg is given by:
   $m_{lower\ leg} = 0.0465 * Total\ Persons\ Mass$. The center of gravity is located at $y = 0.433L$ from the ankle. Be sure to draw the FBD and KD.
   > Hint: Can you calculate the angular velocity and acceleration from the data you were given and the Excel sheet? Hmm… $\theta = \tan^{-1}\frac{y}{x}$
3. Use the relative velocity equation to calculate the velocity of the knee. Use the value for angular velocity that you found above. Compare this knee velocity with the experimental value that can be obtained using the spreadsheet.

ME 212 - Rowing Experiment

You will be analyzing the lower body of someone doing a rowing machine. Using the HMB Lab, we will give you the x-y positions (in mm) of the ankle, knee, and hip as a function of time.

We have provided you with an Excel spreadsheet that will take the first and second derivatives of these positions. Plot the following as functions of time: the velocity and acceleration magnitudes of the hip, the angular velocities of the thigh (HK) and shank (KA), and the angular accelerations of the thigh and shank. These are your *experimental values*.

Now, choose a time when the shank is at approximately 45 degrees from the horizontal. Using the Excel spreadsheet, calculate the experimental the linear velocity and acceleration of the hip at that time. Using this velocity and the lengths HK and KA, use the relative velocity equations to calculate the angular velocity of the thigh HK and shank KA. These are your *calculated values*.

Now, do the same for the linear acceleration of the hip – using the relative acceleration equations, calculate the angular accelerations for the thigh and shank.

Compare your calculated values to the experimental values for the angular velocities and accelerations you found from the Excel spreadsheet, and discuss possible sources of error in your analyses.

ME 212 – Trebuchet Catapult

A trebuchet catapult uses the potential energy of the weight on one end of the device (at point B) to launch a projectile (at point D). As the weighted arm rotates downward, the other end pulls on the sling and the projectile now rotates around end A. The measurements for device components are:

Mass of weights: 555 g (each), 3 total
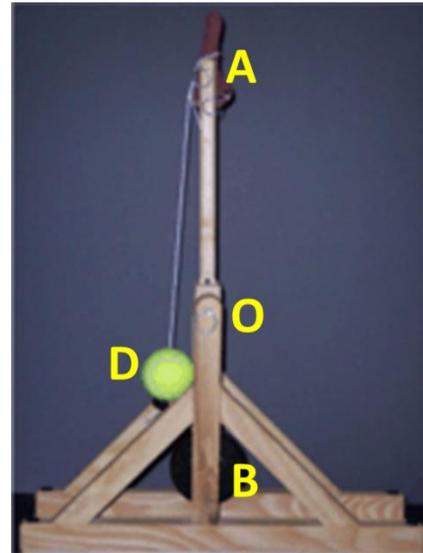Mass of ball: 59 g
Length AB: 620 mm
Length OA: 400 m
Length OB: 220 mm
Length AD: 460 mm
Radius of the weights: 48.2 mm

You are given the position data of each point as a function of time. Use these data and the Excel file that calculates the first and second derivatives to graph the angular velocity of the wooden arm and the angular velocity of the string (AD) as functions of time. Then, using the relative velocity equation, calculate the velocity of the ball at position 2 when the arm is at an angle of 50 degrees. This is your *calculated value* for v_D.   Now use the position data of point D and find its first derivative. This is your *experimental value* for v_D. Compare the two and discuss any errors that might be present.

You can calculate the kinetic energy of the wooden rotating components by using the expression $\frac{1}{2}I_O\omega^2$, where I_o is the mass moment of inertia about point O. This term replaces the full term

$\frac{1}{2}I_O\omega^2 + \frac{1}{2}mv_G^2$ for the wooden components. You still need to use this full term to calculate the kinetic energy of the weights at end B.

If the trebuchet is released from a horizontal position and moves to second position where θ= 50 degrees, use Work and Energy to estimate the overall I_o of the wooden components. You can assume that the change in potential energies of the wooden arm components are negligible compared to the other energies in the system.
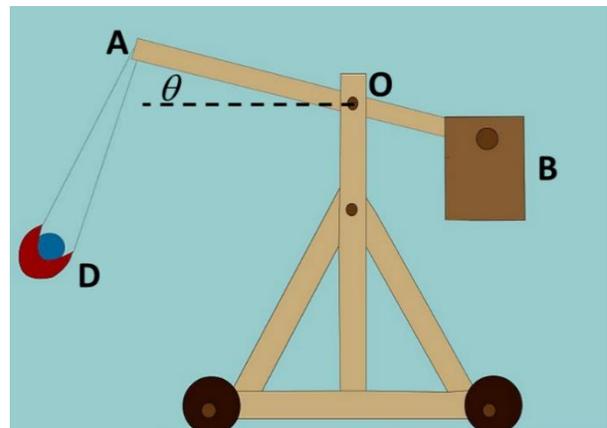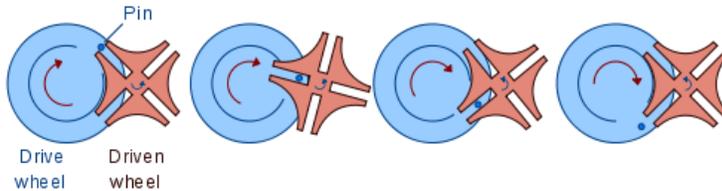
ME 212 – Geneva Mechanism

Image from Wiki

Marker Placement for Geneva in the HMB Lab

A Geneva mechanism is a way to produce intermittent motion; the classic application is old style film projectors. The drive wheel rotates, and a pin on it engages with the slot in the driven wheel. While in contact with the pin, the driven wheel turns in the opposite direction of the drive wheel. Once the pin disengages, the driven wheel is stationary until the pin rotates around and engages the next slot on the driven wheel.

We will place markers on the pin and the center of the drive wheel to characterize its motion. We will also place markers along the driven wheel so you can determine its motion characteristics. You will be able to calculate the positions versus time of these points, and can use the Excel file provided to calculate the first and second derivatives of any set of data.

Thinking back to polar coordinates, plot the r, $\dot{r}$, $\ddot{r}$, θ, $\dot{\theta}$, and $\ddot{\theta}$ of the pin with respect to the center of the driven wheel. Using these, determine the velocity and acceleration of the pin at a point close to $\theta = 30°$. These will be your *calculated values* of the pin using the driven wheel.

Now, plot the angular velocity and angular acceleration of the drive wheel as a function of time. Additionally, plot the x and y distances (values may be + and −) between the pin and the center of the drive wheel. Using these experimental values, determine the value of the velocity and acceleration of the pin (use the relative velocity and relative acceleration equations to do this). Do this for the same instant that you did for the calculated values of the pin using the driven wheel above. These will be your *calculated values* of the pin using the drive wheel.

Finally, compare your values for the calculated values of *v* and *a* for both cases (calculating from the driven wheel vs the drive wheel). Finally, use the position data of the pin and the Excel file to calculate the first and second derivatives (the *experimental values* of v and a). Also compare these to the experimental value for v and a at the same time as your calculated values.

Appendix B

Figure 1B shows an excerpt of the data sheet that students who performed the gait experiment received. The other five experiments produced similar data sheets.

	A	B	C	D	E	F	G	H	I	J	K	L
1		Use m = 82 kg. Evaluate the knee joint forces and moments at t = 1.66 s										
2			Position from Origin (mm)									
3		Time (s)	Ankle		Knee		Hip		Reaction Forces (N)			
4			X	Y	X	Y	X	Y				
5	#Sample								FX2	FY2		
6	175	1.16	-404.605	30.9229	-290.902	477.6623	-161.788	936.6596	-10.49	363.97		Step Begins
7	176	1.167	-404.331	28.47049	-299.859	476.7534	-169.549	935.4846	-10.55	398.64		
8	177	1.173	-403.293	25.86466	-306.894	475.9595	-178.82	934.8945	9.77	339.64		
9	178	1.18	-402.857	25.9381	-315.238	475.0956	-185.741	933.9437	36.88	382.98		
10	179	1.187	-404.369	26.77007	-322.875	474.6888	-193.512	933.6967	58.1	392.87		
11	180	1.193	-409.66	24.56757	-330.866	474.9127	-200.956	933.7286	71.99	359.47		
12	181	1.2	-414.825	21.87846	-338.692	475.6367	-209.23	934.4978	57.91	376.12		
13	182	1.207	-416.683	20.91963	-345.189	476.4727	-216.482	935.3416	53.77	494.9		
14	183	1.213	-417.454	20.01047	-352.804	477.2648	-224.494	936.686	78.91	615.67		
15	184	1.22	-417.243	19.09883	-359.884	478.0733	-230.324	938.3267	103.11	618.69		
16	185	1.227	-417.952	17.65907	-368.273	478.2899	-239.82	938.3452	116.74	600.03		
17	186	1.233	-418.324	17.54378	-377.133	478.3948	-247.408	939.8593	116.89	618.78		
18	187	1.24	-418.843	17.77316	-382.837	478.9083	-254.59	941.1434	113.25	654.01		
19	188	1.247	-418.692	17.71294	-390.499	479.5151	-261.869	942.4699	114.04	686.95		
20	189	1.253	-418.982	17.56696	-397.361	479.8628	-269.595	943.8972	115.47	717.37		
21	190	1.26	-419.174	17.52105	-403.783	480.4936	-275.886	945.3382	117.07	760.02		
22	191	1.267	-419.174	17.52105	-409.298	480.9479	-283.125	946.8142	119.07	804.79		
23	192	1.273	-419.285	17.61258	-414.045	481.3238	-290.702	948.0644	116.09	841.13		
24	193	1.28	-419.285	17.61258	-418.534	480.8792	-299.366	948.7958	111.4	869.56		
25	194	1.287	-419.243	17.72212	-422.151	480.8489	-306.198	949.9839	109.44	890.88		
26	195	1.293	-419.552	17.65933	-426.186	480.5369	-314.24	951.0299	107.19	909.12		
27	196	1.3	-419.585	17.86303	-429.305	480.6127	-321.067	951.5705	104.15	920.11		
28	197	1.307	-419.981	17.99728	-431.575	479.6731	-329.912	952.1901	101.33	921.54		

Figure 1B. Excerpt of positional XY data and kinetic XY ground reaction force data for the gait experiment.