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Generic Stance Geometry Model for Determining Postural Stability Model Motion Induced Interruption Onsets

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***Abstract* -** A generic stance geometry model that is compatible with a three-dimensional extension to the widely-used Graham postural stability model is presented. This model provides a refined method for determining motion-induced interruption onsets; where motion induced interruptions refer to loss-of-balance or impending loss-of-balance events that temporarily interrupt a shipboard crew member from performing their primary task. The developed method is based on determining the location of the normal force required for stability and determining whether that location falls within or without the prevailing instantaneous footprint geometry. The method was validated experimentally using a rigid humanoid model having two distinctly-different footprint geometries both in the laboratory using a six-degree-of-freedom motion base and at sea aboard Canadian Forces Auxiliary Vessel Quest during a heavy weather sea trial conducted in the North Atlantic Ocean. The experimentation on the motion platform validated the stance model for both footprint geometries. A computational model using the proposed stance geometry model was able to determine a similar number of motion-induced interruptions occurring at similar times to the physical experiments. The sea trial experiment further validated the stance model by determining the occurrences of motion-induced interruptions.

***Keywords*:** motion induced interruption**,** MII, Graham model, stance geometry.

1. Introduction

Biomechanical postural stability models were initially developed with the goal of understanding the human sense of balance; however, more recently they have been identified as a potential tool in quantifying the effects of motion environments on human performance. For example, crew members working in a shipboard motion environment are required to perform a variety of physically and mentally demanding tasks such as walking, weapons loading, and lifting (Matthews, 2007). If the ability of the crew to complete these tasks is in any way impaired, the overall efficiency of the crew member decreases resulting in potential increased costs and decreased effectiveness. Also, this may cause the crew member to become so impaired that their personal safety may be at risk. A concept to quantify the performance degradation caused by the crew members' need to adjust balance was introduced by Baitis and Applebee in 1984 (Baitis, 1984). The performance of a crew member is said to be reduced if the person has a motion induced interruption (MII) which is defined as an incident when they must take a step, grab a hold, or stop what they are doing in order to maintain balance (Graham, 1992). The MII concept not only considers the motion of the environment but the effects of this motion on humans who are being analyzed.

The Graham rigid body model was first introduced in the early 1990's (Graham, 1990). The model provides a mathematical approximation of the possible inertial causes of an MII. The model is based on a block having humanoid mass, inertia, and support base properties. An MII is said to occur if the block either has a sliding event or a tipping event. The occurrence of these events is identified by exceeding thresholds based on the properties of the block and gravity. A sliding event is said to happen if the lateral inertial forces and gravitational forces acting on the block exceed the opposing frictional capacity. The frictional capacity is calculated as the force normal to the flat surface multiplied by the frictional coefficient applicable between the surface and the block. The lateral forces are found by a summation of the forces parallel to the flat surface. Initial tests conducted through observation of an unoccupied chair subject to ship motion indicated relatively good agreement between predicted slides for the chair and the actual slides observed. This is to be expected since the chair is simply a rigid body which has no dynamic characteristics to be accounted for (Graham, 1990). A tipping event is said to occur if the moment about one of the model's feet decreases to zero. This tipping model is used to predict when a person will be required to take a step or grab a support to retain balance. These two thresholds are used to model when a person is most likely to take action in order to retain balance.

A research initiative established by the American, British, Canadian, and Dutch (ABCD) Working Group on Human Performance at Sea to explore human factors within the shipboard environment resulted in an extensive set of experiments to investigate the performance characteristics of Graham's model. During the early 1990's, a large data set on human performance in the shipboard environment was produced at the Naval Biodynamics Laboratory (NBDL) in New Orleans. The experiments subjected 15 participants to two levels of ship motion severity using a large ship motion simulator platform. The subjects were required to complete a number of tasks during the motion profiles. Human postural response data from the tasks, consisting of standing facing port and standing facing aft, were used by Lewis and Griffin to check the validity of the rigid body model and to investigate the potential application of more complex models to MII prediction such as parametric methods (Maki, 1996). From these experiments it was proposed that Graham's model could be tuned to more accurately predict MIIs by empirically choosing tipping and sliding thresholds to match experimental MII occurrences. A similar adjustment process was recommended for parametric stability models. Initially, for a parametric model, MIIs were defined as points at which the centre of pressure exceeded base of support limits. In practice the usable base of support region was found to be smaller than the theoretical maximum value. Based on this, it makes sense to adjust the parametric model's MII threshold accordingly.

A second series of experiments based on the initial NBDL investigations was conducted by the United Kingdom's Defence Research Agency using a large motion simulator (Crossland, 1996, 1997, 1998). The ability of the simulator used in this case to provide motion cues in five degrees of freedom provided the opportunity to generate a set of postural response data relating to frontal plane MIIs. During the experiment, subjects were required to complete several different tasks such as walking, weapon loading, and standing while being subjected to the NBDL motion profiles. As suggested by the NBDL experiments, empirical MII thresholds were determined for the rigid body MII model. In addition to the standing tasks, empirical model thresholds were determined for all of the experiment tasks despite the fact the model does not physically represent them. The tuned model was found to provide reasonable predictions of MII occurrences in all cases although it underpredicted at high MII rates. A statistical model of MII occurrences was also investigated using the experimental data.

The Graham stability model was expanded to three dimensions by Morris and Langlois (Morris, 2012). The mathematical model was expanded to calculate the forces and moments in three dimensions. The three-dimensional model was validated using two methods: first, computationally with the Langlois inverted pendulum model (Langlois, 2010); and second, experimentally using a physical apparatus on a six-degree-of-freedom motion platform. The two validation methods determined that the model was capable of calculating the reaction forces and moments for stability.

This paper introduces a model for determining the number of MII occurrences using a generic footprint model. This model was developed using the three-dimensional Graham model to calculate the postural stability forces and moments. The footprint model was validated through experimentation in Carleton University's Applied Dynamics Lab on a six-degree-of-freedom motion platform, as well as at sea aboard Canadian Forces Auxiliary Vessel (CFAV) Quest on a North Atlantic Sea trial conducted in November 2012 (Bourgeois, 2013). The results from the experimentation showed that the total number of MIIs as well as the occurrence times of the MIIs were predicted similarly to what was observed.

2. MII Definition and Concept

There are four theoretically-possible modes of MII onset associated with the Graham stability model: sliding, tipping in the frontal plane, tipping in the sagittal plane, and yawing. Four parameters are used to identify these MII events. These parameters are defined in a general form such that they quantify the severity of the respective sea conditions without presupposing particular threshold values. The concept of an MII was first presented by Baitis and Applebee (Baitis, 1984), and then subsequently generalized by Langlois (Langlois, 2010) to the format used in this paper. The stability model used in conjunction with this model was the three-dimensional Graham model developed by Morris and Langlois (Morris, 2012). The spatial Graham model solved for the reaction forces and moments at the model's interface to the deck. The reaction forces calculated from the model are denoted as F_x, F_y, and F_z, and the reaction moments are denoted by M_x, M_y, and M_z.

In the case of sliding, the parameter called the sliding index P_{slide} is given by,

$$P_{slide} = \frac{\sqrt{F_x^2+F_y^2}}{|F_z|} \tag{1}$$

Sliding is expected when the value of P_{slide} exceeds the prevailing coefficient of friction μ at the interface between the dynamic stability model and the deck.

In the generalized case of tipping, the model may tip in three directions: in the frontal plane, in the sagittal plane, and by yaw in the deck plane. The relevant parameters for the frontal plane tipping index $P_{frontal\ tip}$, sagittal plane tipping index $P_{sagittal\ tip}$, and the yawing index P_{yaw} are given by

$$P_{frontal\ tip} = \frac{|M_x|}{|F_z|} \qquad P_{sagittal\ tip} = \frac{|M_y|}{|F_z|} \qquad P_{yaw} = \frac{|M_z|}{|F_z|} \tag{2}$$

Tipping is expected when the value of $P_{frontal\ tip}$ exceeds a threshold corresponding to the effective stance width, $P_{sagittal\ tip}$ exceeds a threshold corresponding the effective stance length, or when the value of P_{yaw} exceeds a threshold corresponding to the effective stance diameter.

In summary, the reaction forces and moments determined from the stability models, are used to calculate these MII indices. They provide the means for estimating likely onsets of MII events for rectangular footprints.

2. 1. Modified Indices for a Generic Footprint

The Graham block model's only means of resisting any applied moment about the *x* and *y* directions is through the location of the normal force. If the normal force needs to be applied outside the bounds of the footprint, the model is said to tip over. The stance footprint available to generate a sufficient restoring moment was defined arbitrarily in order to generalize the tipping index. The required coordinates of the normal force are calculated based on this generalized footprint.

Assuming the postural model is no longer attached to the deck at the single point below the centre of mass, the normal force intersects the deck at a time-varying location, defined by *x* and *y* coordinates, appropriate for countering the tipping moments about the *x* and *y* directions. The corresponding distances required to counter the *x* and *y* moments are

$$r_x = \frac{|M_y|}{|F_z|} \qquad r_y = \frac{|M_x|}{|F_z|} \tag{3}$$

where r_x is the distance in the *x* direction of the normal force F_z from the centre of mass and r_y is the distance in the *y* direction of the normal force from the centre of mass; all expressed in the model coordinate frame. The geometry is illustrated schematically in Figure 1.

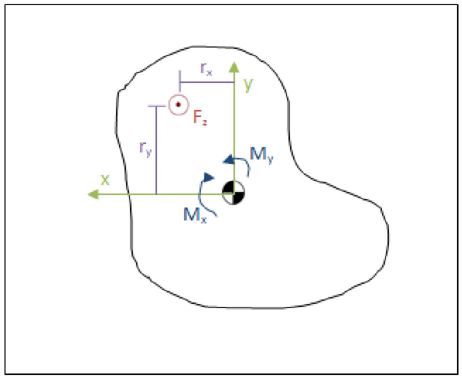

Fig. 1. Normal force location to counteract the tipping moments on the block model with a generic footprint

The calculated distances r_x and r_y define the location of the normal force on the ship deck in the model frame relative to the centre of mass. In order to determine a tipping incident, the next requirement is to determine whether the *x* and *y* location of the normal force is contained within the footprint.

It is assumed that the footprint of the spatial Graham model (or an alternative model) is defined by *n* points that, when connected in sequence, define a closed polygon. Each vertex of the polygon is required to be defined using Cartesian coordinates relative to the centre of mass. The location of the normal force would be either inside or outside the footprint polygon. An algorithm to find whether the normal force is within the polygon requires the angles between the point (r_x, r_y) of the normal force and the n^{th} and $n+1^{th}$ vertex points as determined in any coordinate system co-planar with the deck. Summing all the angles calculated between the vertices in this way results in 360^o if the normal force is within the footprint, and 0^o if the normal force is outside the footprint (Heckbert, 1994). These values can be used as indicators for determining tipping events.

3. Implementation of the Stance Model with GRM3D

The MII stance model is used in conjunction with a postural stability model. The stability model calculates the reaction forces and moments at the base of the model and the MII model determines the predicted onset of MIIs. The MII model was implemented within the three-dimensional Graham model (GRM3D) executable developed by Morris and Langlois (Morris, 2012). The Graham model has been validated for calculating the reaction forces and moments at the base. The MII model then uses the forces and moments calculated from that model to calculate the location of the normal force. The algorithm then checks if the normal force is within the footprint at each time step.

4. Experimental Apparatus

The experimental apparatus used to validate the MII footprint model is based on the Graham model of a block with humanoid mass and inertial properties. The apparatus is cut out of three-quarter inch SPF plywood in the shape of a stylized humanoid similar to the one originally illustrated by Graham (Graham, 1992). Three layers of plywood were laminated in order to achieve the desired thickness of the humanoid section. A scaled drawing of the assembled apparatus is provided in Figure 2. Two separate contact footprints were constructed for the stance of the model, one with the feet side by side and one with the feet staggered with one foot ahead of the other. A scaled drawing of the footprints is also provided in Figure 2. The side by side stance should correspond to the results from the Graham model as the footprint bounding box can be thought of as having rectangular edges. The staggered footprint was also implemented because it is a common alternative stance to the side by side stance.

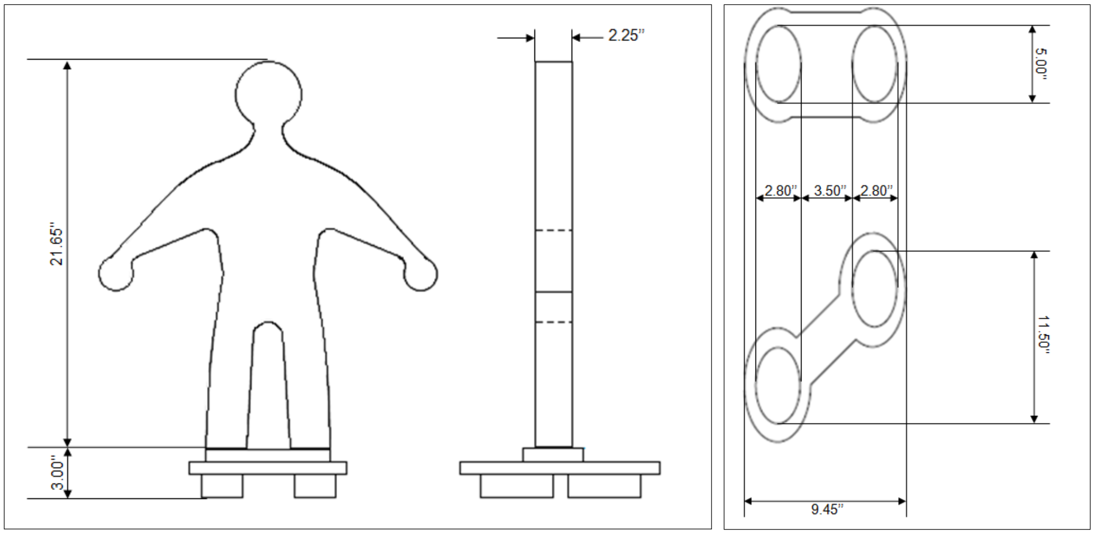

Fig. 2. Scaled drawing of the MII man assembled apparatus with staggered footprint attached and the straight and staggered footprint configurations.

To measure the time and direction of the MII occurrences for the physical apparatus, on/off contact switches are attached along the outside perimeter of the footprint. Each of the switches is connected to an Arduino Mega 2560 microcontroller. This microcontroller is programmed to identify which of the switches are depressed at any given time. The switches have been attached to the apparatus such that there is a known angle from the centre of mass to the individual switch locations. From the switch locations, the direction of tipping is known. It must be noted that this model is instrumented only to detect tipping MIIs of the stability model. Any sliding or yawing MII events must be observed manually. This is not particularly limiting as tipping MII events usually occur first with realistic interface parameter values.

5. MII Detection with Stance Geometry Validation Experiments

The goal of these experiments was to validate that the MII events predicted by the stance model agreed in number and occurrence time with those measured during the experiment. The first series of experiments consisted of placing the experimental apparatus on a six-degree-of-freedom motion platform and then to subject the apparatus to simulated ship motions. The simulated motions used for the validation experiments corresponded to seas characterized by sea state five with long-crested waves of 10 second modal period. The simulated ship is travelling at a heading of forty-five degrees relative to the wave direction. The resulting ship motions were predominantly in the roll direction. To keep the motions within the platform limits, translational motions were excluded. Each of the two stance geometries was run with the apparatus facing 0, 45, and 90 degrees relative to the simulated ship's longitudinal axis.

The data collected from the Arduino microcontroller was written to an output file where a depressed switch was indicated by a 1 versus a 0 if not depressed. This file was interpreted manually in order to count the MIIs and the time when each MII occurred. An MII was said to occur if the depression of the switches changed. It was also necessary to investigate the rate of change of the switches because the model would occasionally sway back and forth prior to stabilizing. Based on the definition of an MII, each swaying motion in such a case should not be considered as a distinct MII because they are all considered a part of regaining balance following the initial MII. The MII event is used to determine the onset of imbalance, and the count is not allowed to proceed until balance is restored. In reality, this means that if a person has lost balance and remains unbalanced for a long time it only counts as one MII event until full balance is restored. This is interpreted in the data by only investigating the time at which the switch depression is changed and held in this state for over two seconds. This was assumed sufficient time to say that full balance was restored.

The spatial Graham model simulation was run using the same ship motions as in the physical experiments. The physical parameters of the MII experimental apparatus are also known and used for the simulation. The results from the simulation are provided in a similar format to the results from the switches on the physical apparatus. In order to determine the occurrence of an MII event this data was visually checked. An MII was said to occur if there was a change in the normal force position from inside the footprint to outside the footprint. Times of the MII events were identified by the times at which the normal force would change from being inside to being outside the footprint. Balance was said to be restored if there was no change in stance value for 2 seconds.

6. Comparison of Results from the Laboratory MII Stance Experiments

This section presents the comparison of the results from the physical experiments with those from the simulation. Results presented for both of the stances considered: the side by side (also named straight), and the staggered footprints. A complete set of straight results will be presented first.

The motion was run for 100 seconds to collect the data. The ship motions were used to run the simulation and the number of MIIs was determined from the output based on whether the normal force was within the stance geometry or not. The MIIs from the physical experiment and the simulation with the model at zero degrees were counted and the times of occurrence of the MIIs can be seen in Table 1.

Table 1. MII occurrence times for the straight stance and staggered stance at 0 degrees offset obtained from the experimental apparatus and simulation.

	Staggered Stance		Straight Stance	
MII Number	Occurrence Time Experimental	Occurrence Time Simulation	Occurrence Time Experimental	Occurrence Time Simulation
1	2.87 sec	1.64 sec	3.1 sec	2.62 sec
2	4.76 sec	6.26 sec	5.96 sec	-
3	9.66 sec	12.23 sec	72.65 sec	70.31 sec
4	15.23 sec	17.13 sec	82.45 sec	79.75 sec
5	20.80 sec	-		
6	-	30.12 sec		
7	-	36.20 sec		
8	39.49 sec	40.56 sec		
9	43.87 sec	44.87 sec		
10	48.64 sec	54.51 sec		
11	61.69 sec	58.53 sec		
12	66.36 sec	63.36 sec		
13	70.76 sec	68.21 sec		
14	76.01 sec	73.17 sec		
15	79.19 sec	78.45 sec		
16	80.95 sec	-		

7. Validation against Footprint Model Experimentation on CFAV Quest

A heavy-weather sea trial was conducted from November 20th through November 28th, 2012 aboard CFAV Quest, a research vessel operated by DRDC Atlantic, in the North Atlantic Ocean approximately 60 nautical miles South of Halifax, Nova Scotia, Canada. A postural stability experiment from Carleton University's Applied Dynamics Lab was one of two experiments conducted during the trial. Among other related experiments comprising the Carleton experimental suite, the MII man experimental apparatus was brought on board in order to collect data for the footprint model. It was set up on the deck in the lab space provided on the ship. The data collection was similar to the data collected in the Applied Dynamics Lab at Carleton. The ship motion was measured with a six-degree-of-freedom inertial sensor that recorded accelerations, angular rates, and orientation of the deck. The day of the data collection, the waves were measured at an approximate significant wave height of 2.5 m (low sea state 5) which provided MII events but allowed the apparatus to maintain balance for most of the experimental time. The data was collected in 2 minute sets where the apparatus was oriented at 0, 45, and 90 degrees relative to the longitudinal axis of the ship. Both the straight and staggered footprints were used.

The number of MIIs were counted from the data obtained using the switches and were compared to the corresponding results from the simulation. The simulation was run using the ship motion collected from the inertial sensor and the physical parameters tabulated in the previous section. The occurrence of MIIs for the straight stance at 90 degrees relative to the longitudinal axis of the ship with beam seas can be seen in Table 2. Table 2 also provides the MII occurrences for the staggered stance at 0 degrees relative to the longitudinal axis of the ship with beam seas. The data from other model orientations and ship headings produced similar results. These results further validate the footprint model based on experimentation on a ship in real world conditions while at sea.

Table 2. MII occurrence times for the straight stance at 90 degrees and the staggered stance at 0 degrees in beam seas obtained from the experimental apparatus on Quest and simulation.

	Straight Stance		Staggered Stance	
MII Number	Occurrence Time Experimental	Occurrence Time Simulation	Occurrence Time Experimental	Occurrence Time Simulation
1	4.41 sec	5.8 sec	32.7 sec	31.41 sec
2	8.08 sec	-	42.76 sec	42.3 sec
3	26.4 sec	28.12 sec	-	52.75 sec
4	31.9 sec	30.55 sec	68.6 sec	64.72 sec
5	42.2 sec	40.44 sec	78.1 sec	72.68 sec
6	55.9 sec	47.27 sec	87.7 sec	82.04 sec
7	65.3 sec	61.03 sec		
8	79.9 sec	66.25 sec		
9	90.1 sec	85.83 sec		

8. Discussion

The results from the validation experiments show that the simulation is able to determine the time and number of MII occurrences. There are a few potential sources of error in both the experimental and simulation MII counts. One of the major potential sources of error with the experimentation in the lab is that it was not safe to approach and rebalance the apparatus when the motion platform was running. Some of the additional MIIs from the experiments could be caused by the inability to upright the apparatus while a run was being conducted. On Quest, the apparatus was balanced upright after each MII and the number and times of the MIIs are more consistent with the simulated data. Another point of interest with the results is that there is a delay in the time of the MII events counted from the experiment. This error is assumed to result from how the time is recorded with the Arduino. The timing of the results from the Arduino was based on counting milliseconds since the last communication. This function is also not connected to the computer clock and thus the timing might be different on board the Arduino. The delay could also be the result of the physical model having to accelerate over time before it could move enough to trigger the switch. The effect of the acceleration from the simulation would be instantaneous and would not experience that delay. However, overall, the data recorded from the experiments and the results from the simulation were very similar.

From a simulation perspective, the models could be enhanced in order to have a footprint that changes over time. For this to be accomplished, the determination of whether the normal force is within the footprint needs to be embedded into the computational model. Currently that is done through post-processing of the data. If the motion over time of the footprint is known, then at each time step it can be determined if the normal force is within the footprint or not, and thus whether an MII has occurred. This could be used for models that would count the MII occurrences of a person walking on deck. All that would need to be known is how the footprint changes over time and the position on deck over time. From that information, the number of MIIs could be counted. This means that the simulated model would not have to remain fixed to the deck and could be moving and changing over time.

9. Conclusion

A model was developed to determine the onset of MIIs for arbitrary stance geometry. The model was implemented to work in conjunction with the three-dimensional Graham model developed by Morris and Langlois. However, in its current form, it can readily be adapted to other MII dynamic models. The model was validated experimentally at Carleton University in the Applied Dynamics Lab on a six-degree-of-freedom motion platform using an apparatus with two footprint geometries. It was also validated using heavy-weather sea trial data collected aboard CFAV Quest. The results obtained from the experimentation and corresponding simulation show that the model correctly determines the number and timing of MII events. From these results the generic footprint model has been validated.

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