Low-level Fall Simulation: Toddler Falling From Chair

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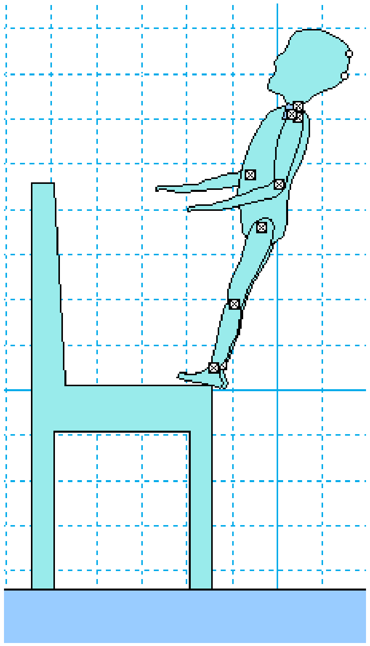
11 June 2012

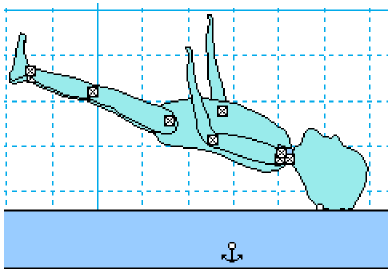
(rev. 7/9/2013)

Situation

Toddlers occasionally fall from chairs or beds and hit their heads on the floor. They might simply lose balance and lean back too far or accidently step off attempting to regain balance. Resulting impacts have potential for grievous injury and even death.[1]

An extreme case occurs if the joints are frozen by fear or defiance and the head hits first. The model predicts an initial vertical impact speed v_y = 4.5 m/s ≈ 10 miles/hour. Note that this is almost $v_y = \sqrt{2gh} = 4.8$ m/s predicted by free-fall for the point simply dropping $h = 1.2\ m$ and the acceleration due to gravity $g = 9.8\frac{m}{s^2}$.





Refinements

The following simulation allows flexible joints and other variable parameters to demonstrate one of countless possible scenarios between the previous rigid extreme and cases where the head does not even hit the floor. It is intended as a demonstration aid that is more realistic than an artist's conception.

- An initial horizontal backwards step at 1.0 m/s is used and results in a first cranial impact speed of 5.4 m/s. This **exceeds** that predicted previously for free-fall, partly due to the initial speed.

- Derived results such as accelerations depend on contact time as explained in Appendix A.

- Prediction reliability is limited by the choice of model parameters given in Appendix B (mass distribution, joint approximations, elasticity and friction) . Any changes to these parameters, initial posture, or rigidity of linked segments may change the outcome significantly.

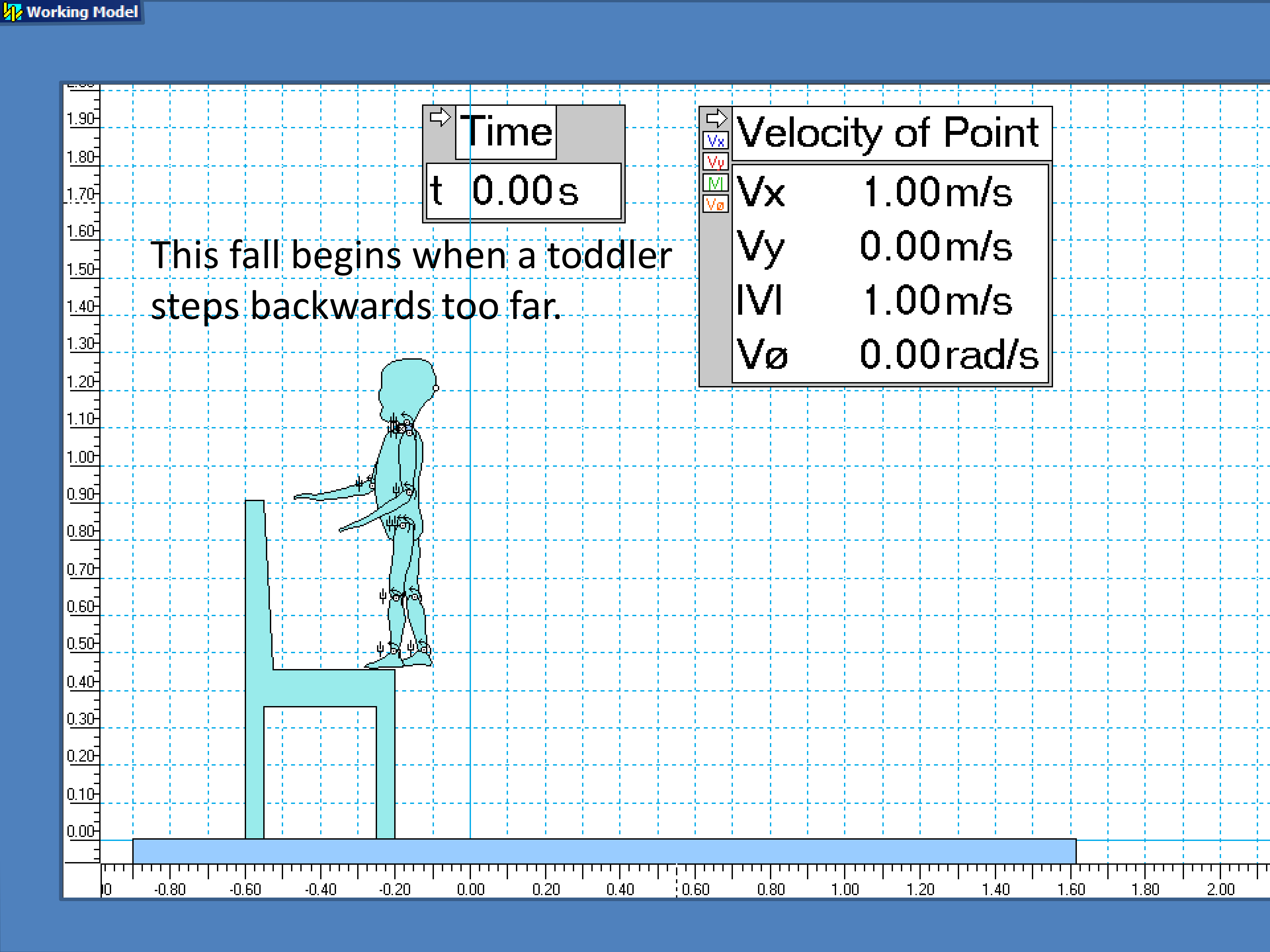
- The simulation is based on average dimensions for an 18-month old child crash-test dummy[2] with a stature of 0.81 m (32 inches) and mass of 11.0 kg (24.3 pound), including a 2.6 kg (5.8 pound) head. More details are given in Appendix B.

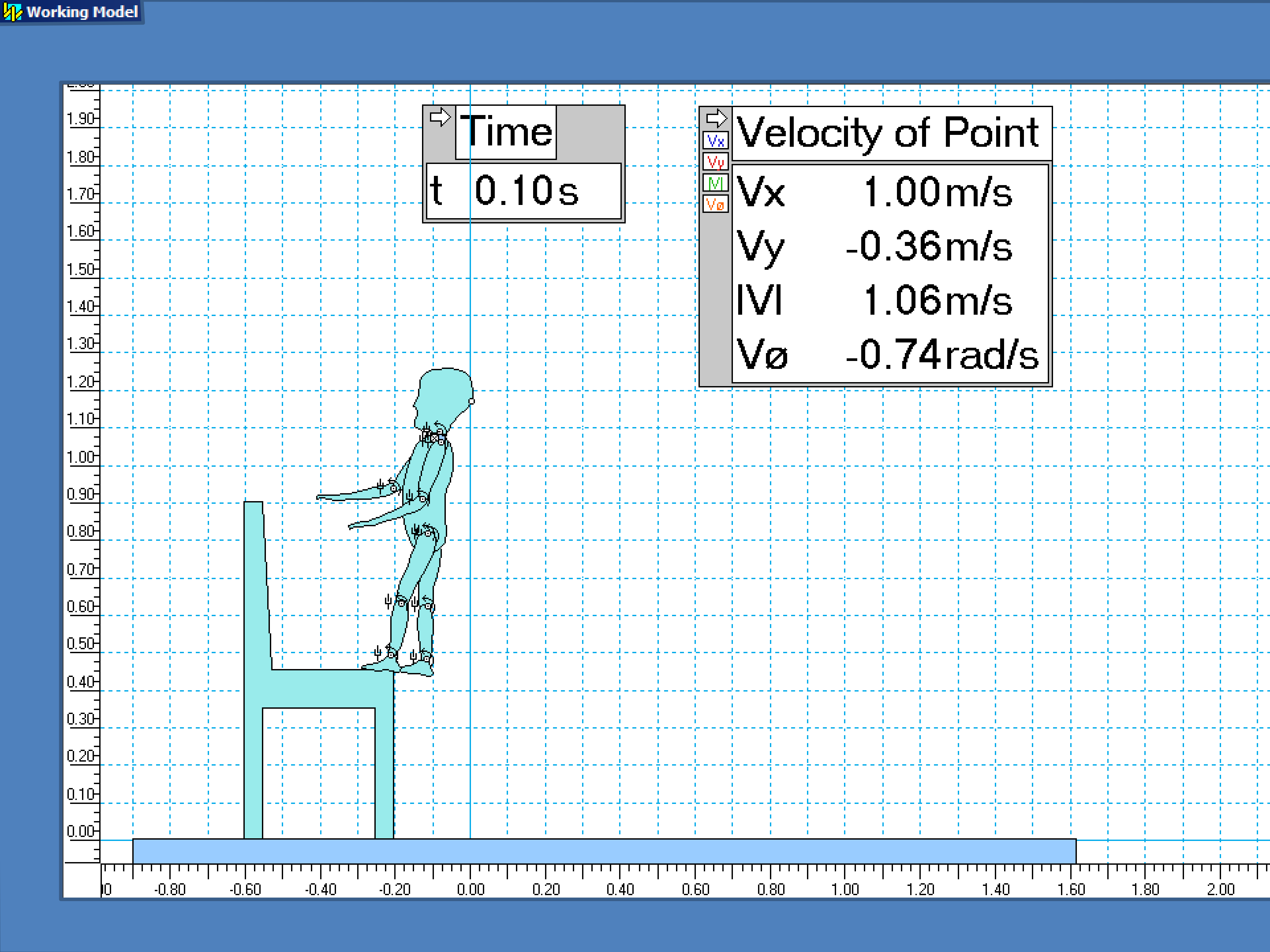
- Scale dimensions are in meters. Velocities are displayed for the initial cranial impact point. Multiply values in m/s by 2.24 to convert into miles/hour.

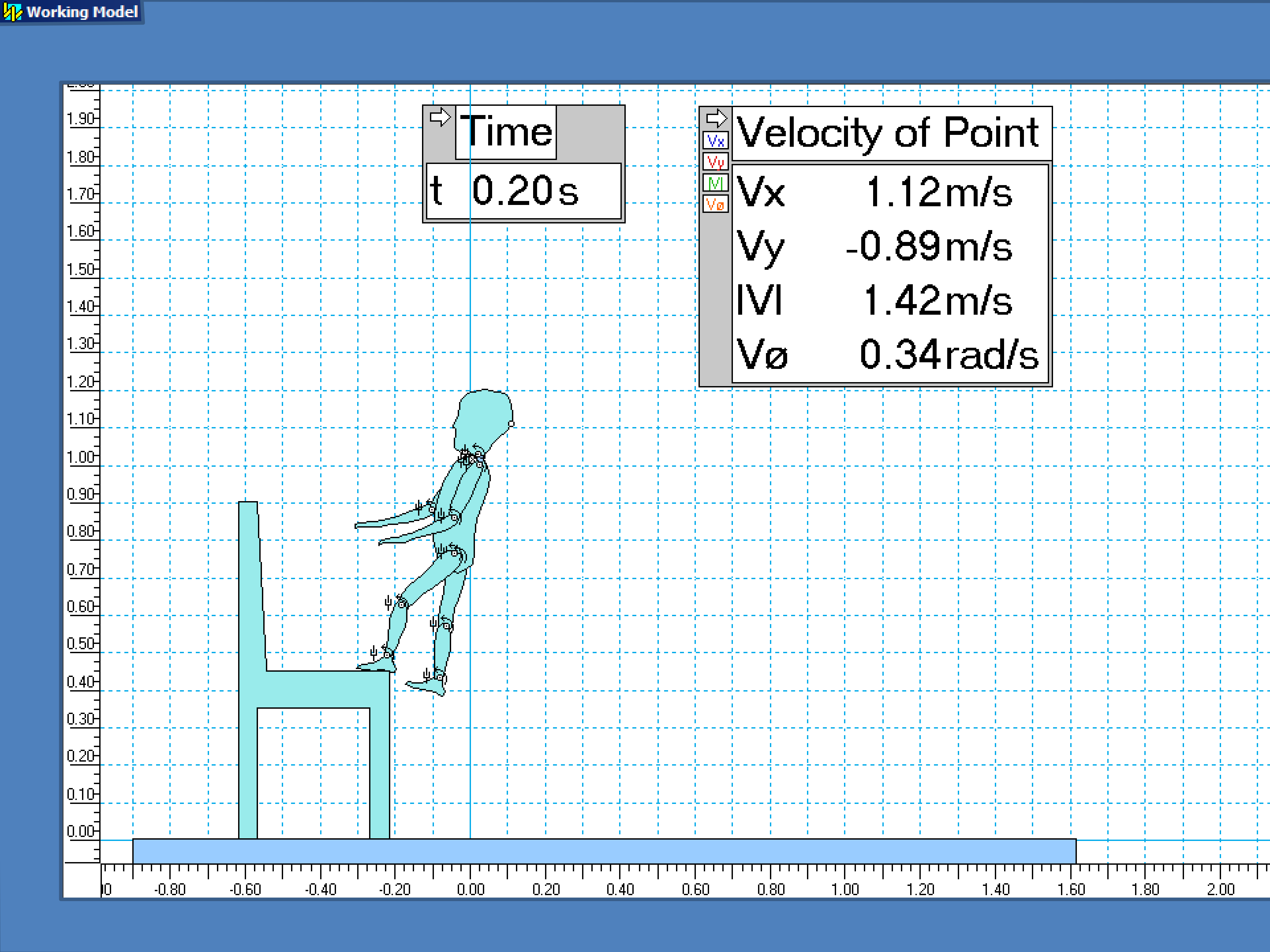
- The integrity of the software was checked by generating accurate predictions for cases with known analytical solutions. These were free-fall for a ball and toppling a long thin vertical rod about an ideal axis fixed at the bottom.

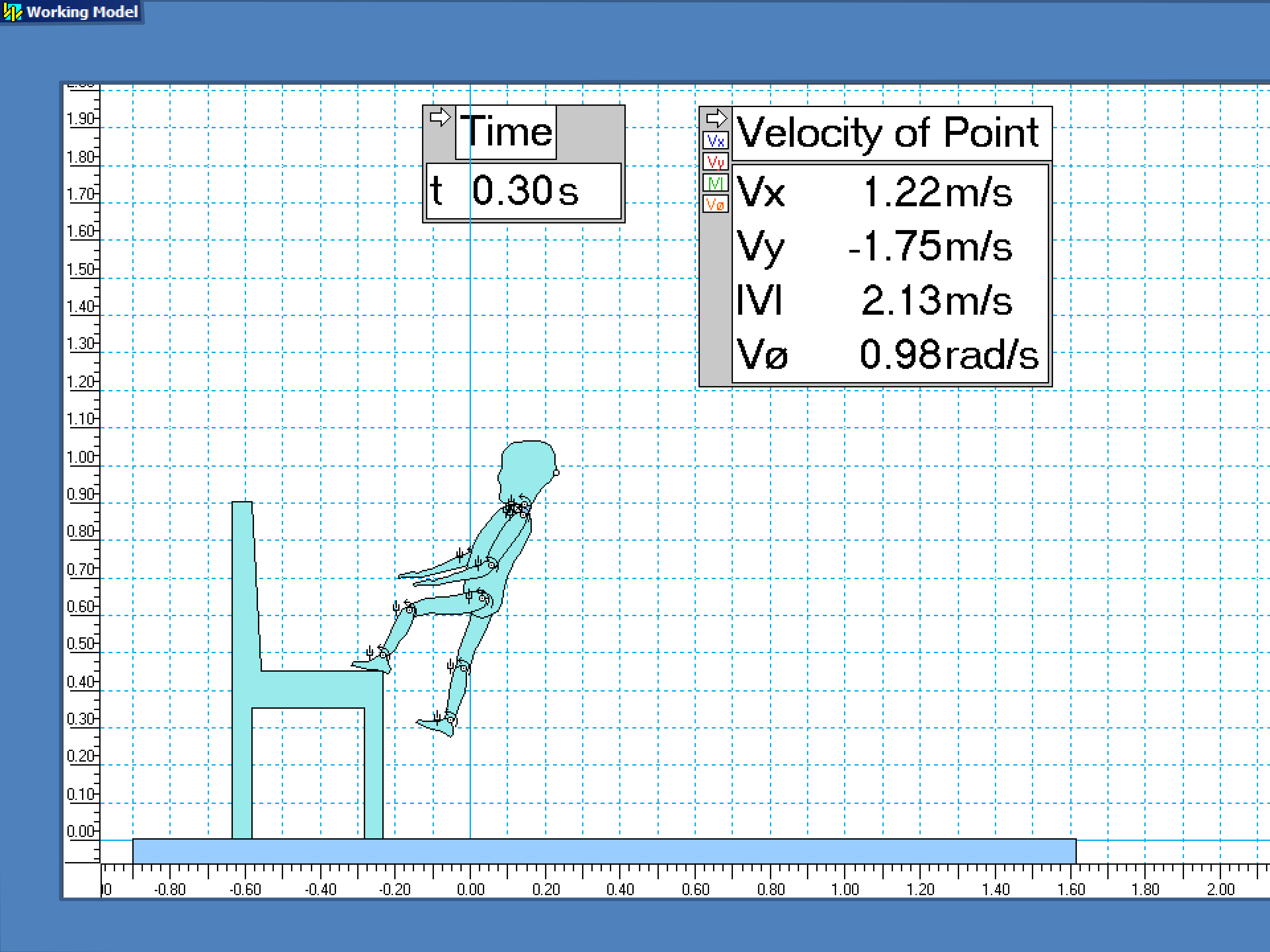
- Other computer simulations, physical models and video analysis are invited for comparison to help evaluate this simulation.

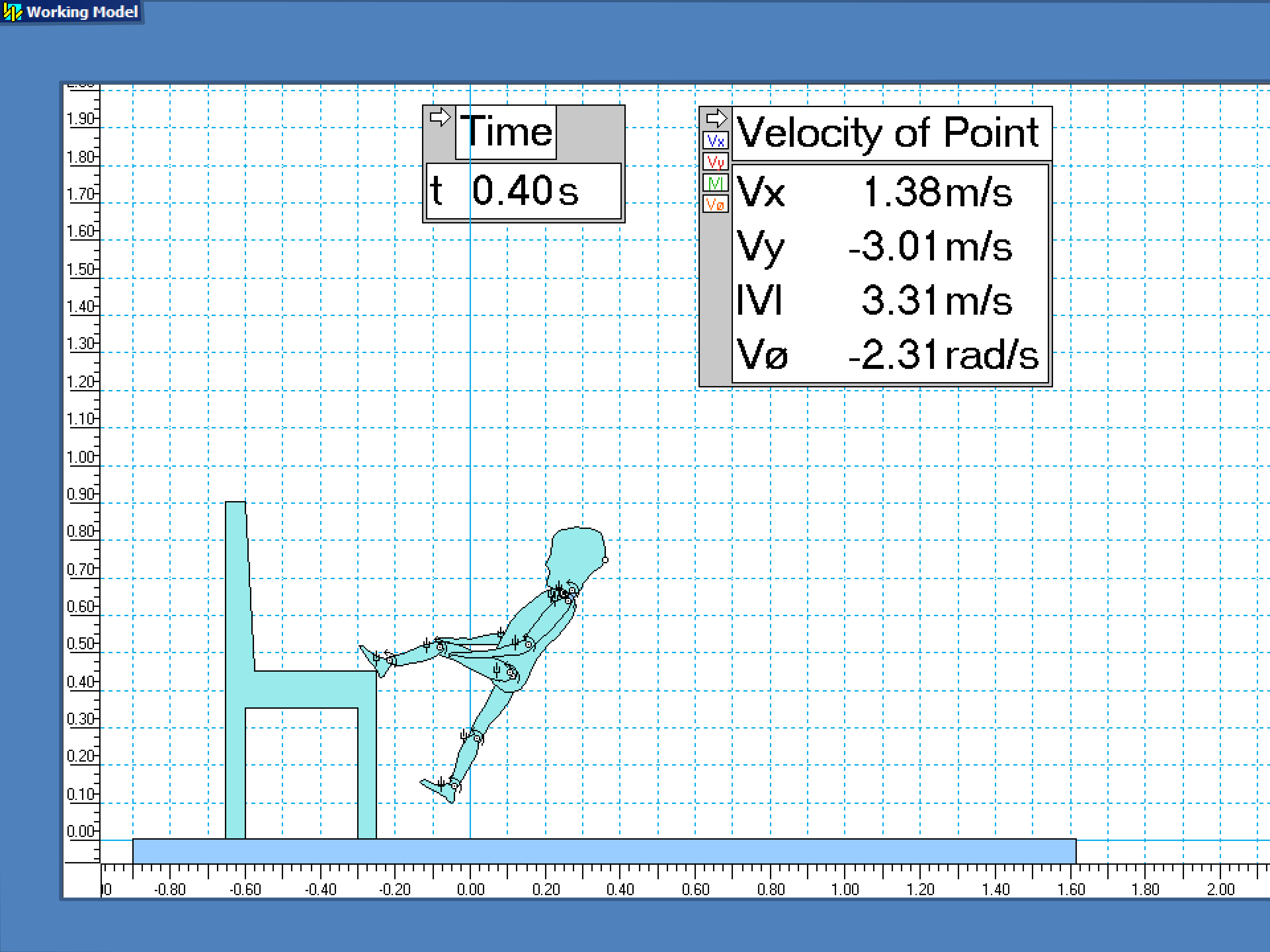
This fall begins when a toddler steps backwards too far.



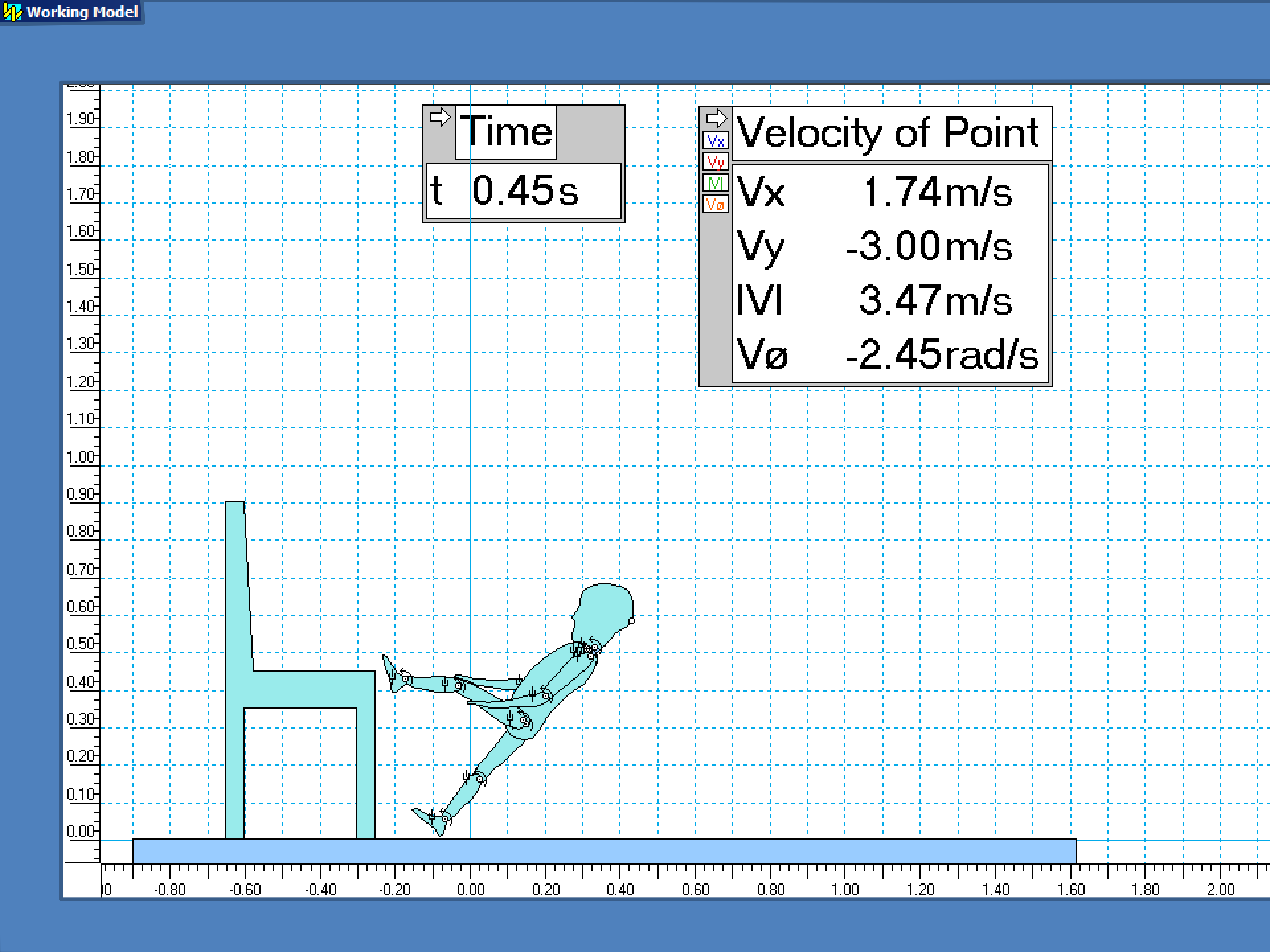

Working Model
Time
t 0.10s
Velocity of Point
Vx 1.00m/s
Vy -0.36m/s
|V| 1.06m/s
Vø -0.74rad/s

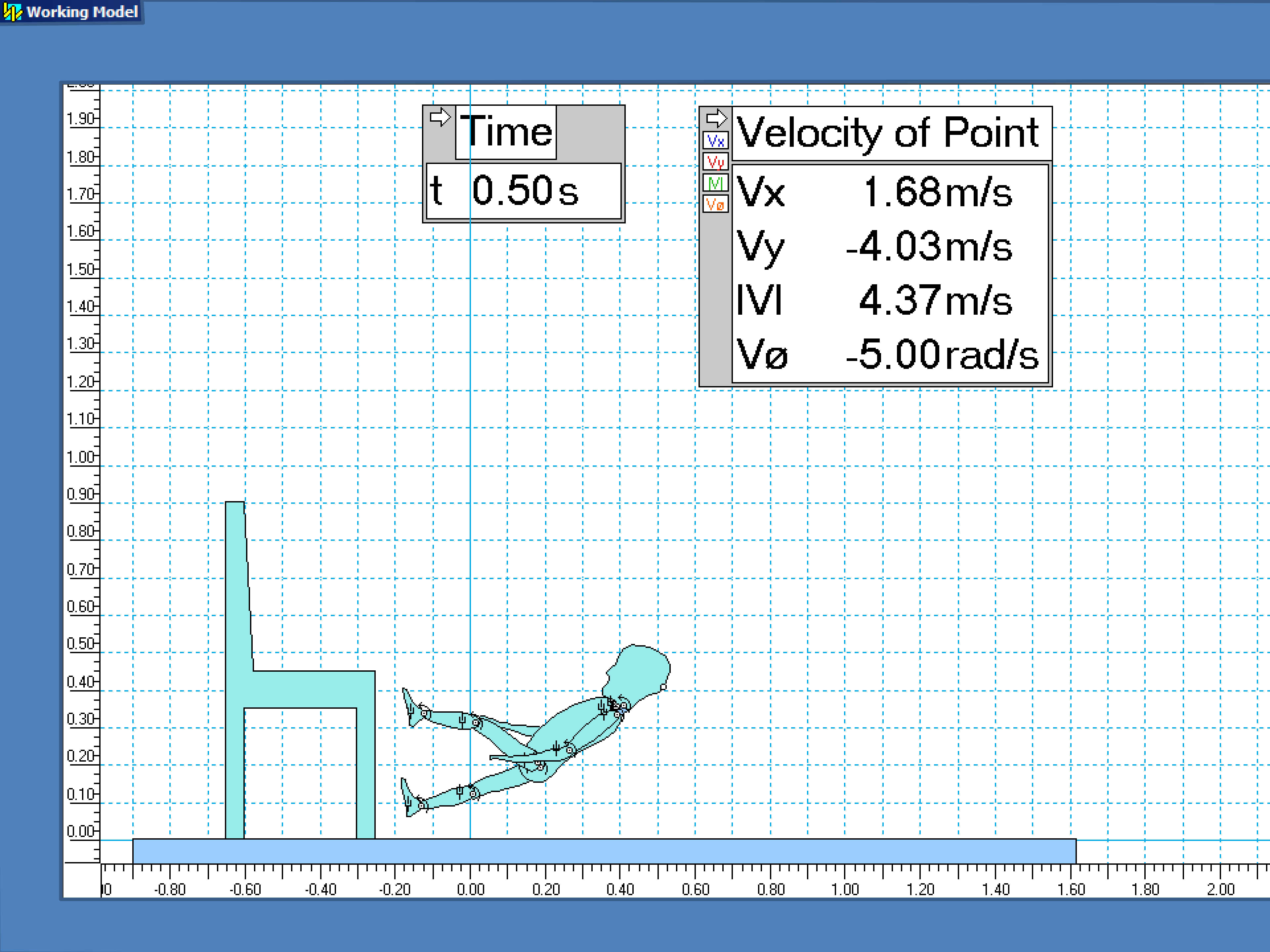

Working Model
Time
t 0.20 s
Velocity of Point
Vx 1.12 m/s
Vy -0.89 m/s
|V| 1.42 m/s
Vø 0.34 rad/s
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00

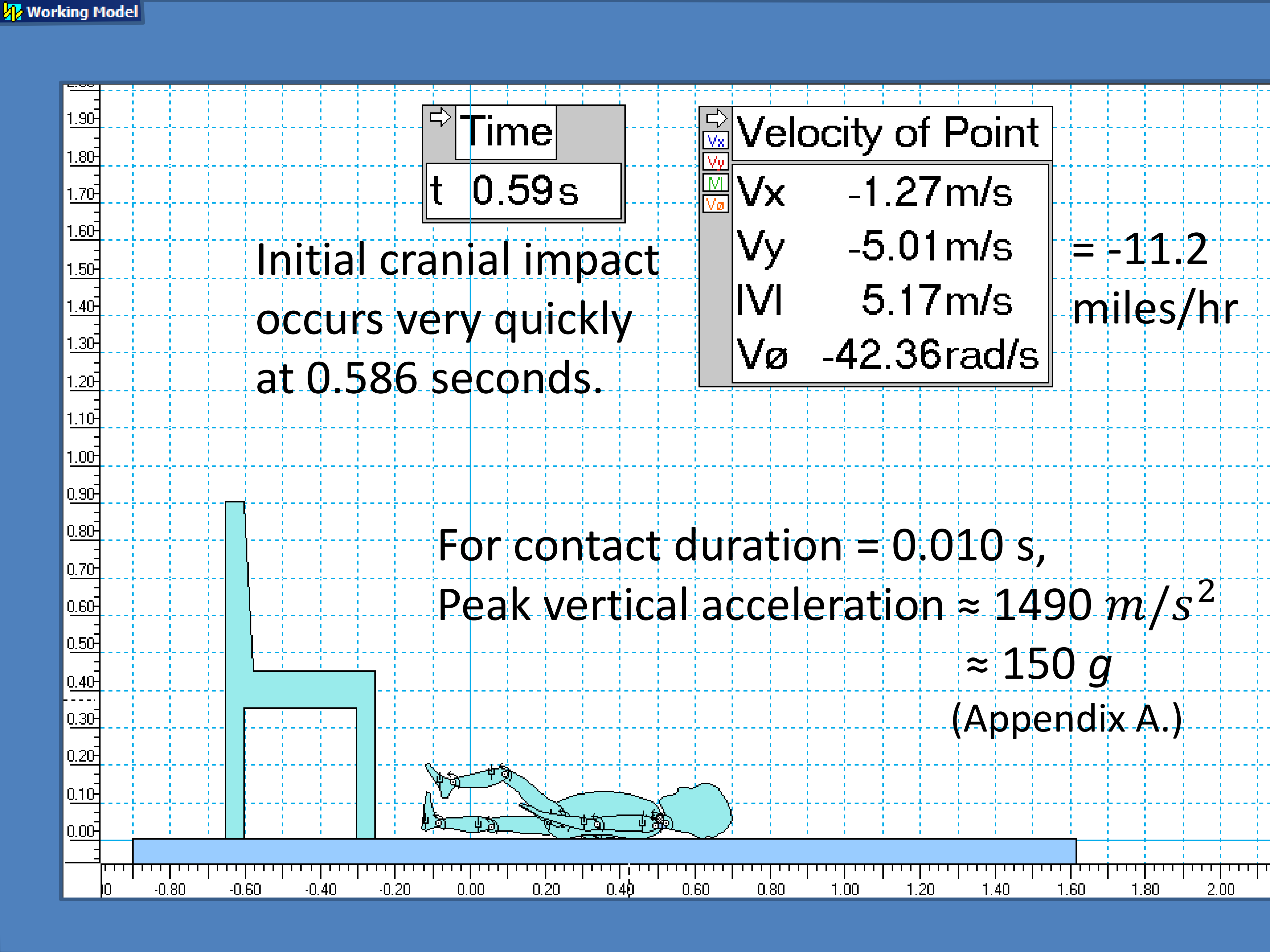

Working Model
Time
t 0.30 s
Velocity of Point
Vx
Vy
M
Vø
Vx 1.22 m/s
Vy -1.75 m/s
|V| 2.13 m/s
Vø 0.98 rad/s
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00



Working Model
Time
t 0.40 s
Velocity of Point
Vx 1.38 m/s
Vy -3.01 m/s
|V| 3.31 m/s
Vø -2.31 rad/s


Working Model
Time
t 0.45s
Velocity of Point
Vx Vy M Vø
Vx 1.74m/s
Vy -3.00m/s
|V| 3.47m/s
Vø -2.45rad/s
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00


Working Model
Time
t 0.50 s
Velocity of Point
Vx 1.68 m/s
Vy -4.03 m/s
|V| 4.37 m/s
Vø -5.00 rad/s
Vx
Vy
|V|
Vø
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.80 -0.60 -0.40 -0.20 0.00 0.20 0.40 0.60 0.80 1.00 1.20 1.40 1.60 1.80 2.00



= -11.2 miles/hr

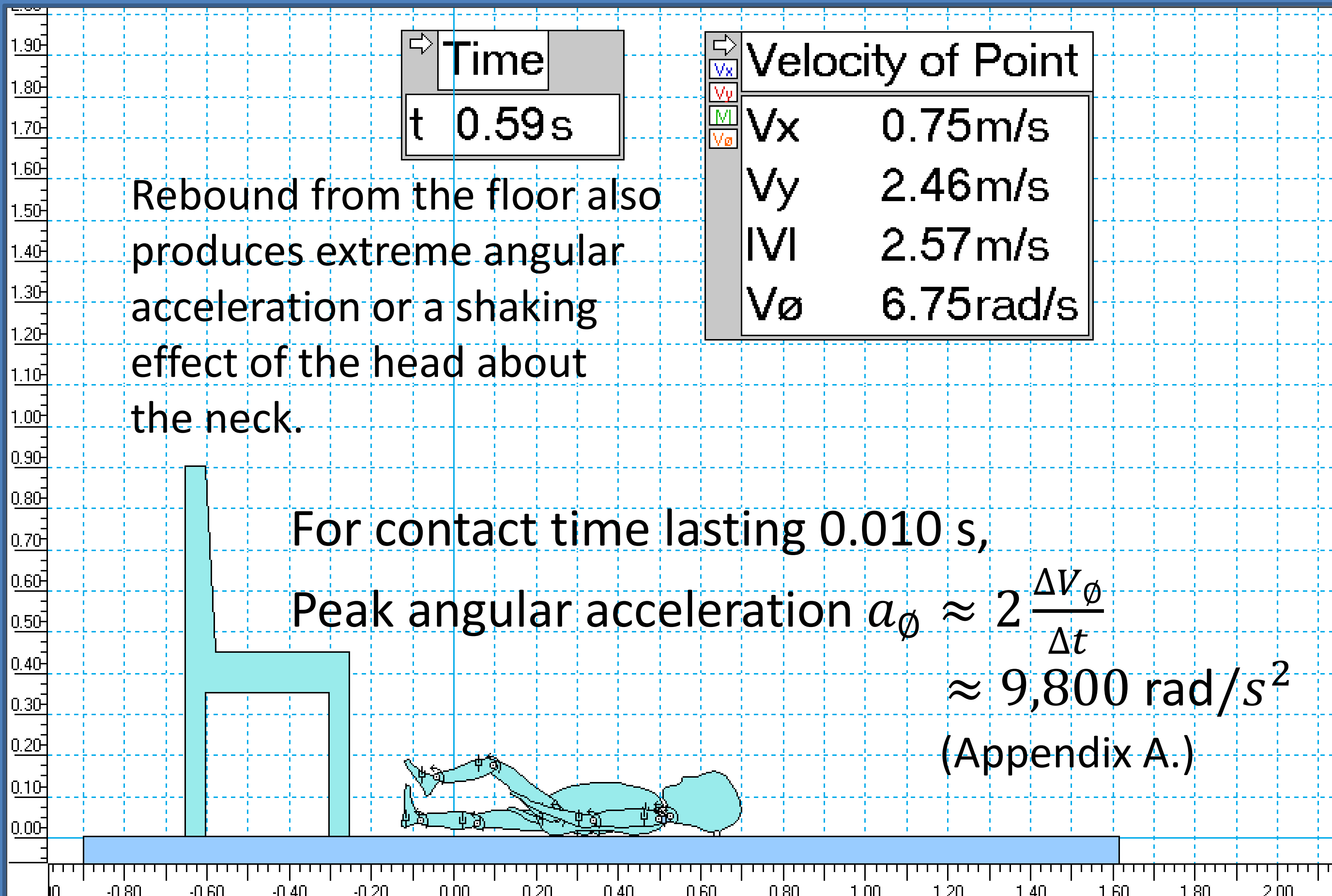
Initial cranial impact occurs very quickly at 0.586 seconds.

For contact duration = 0.010 s,

Peak vertical acceleration ≈ 1490 m/s^2

≈ 150 g

(Appendix A.)



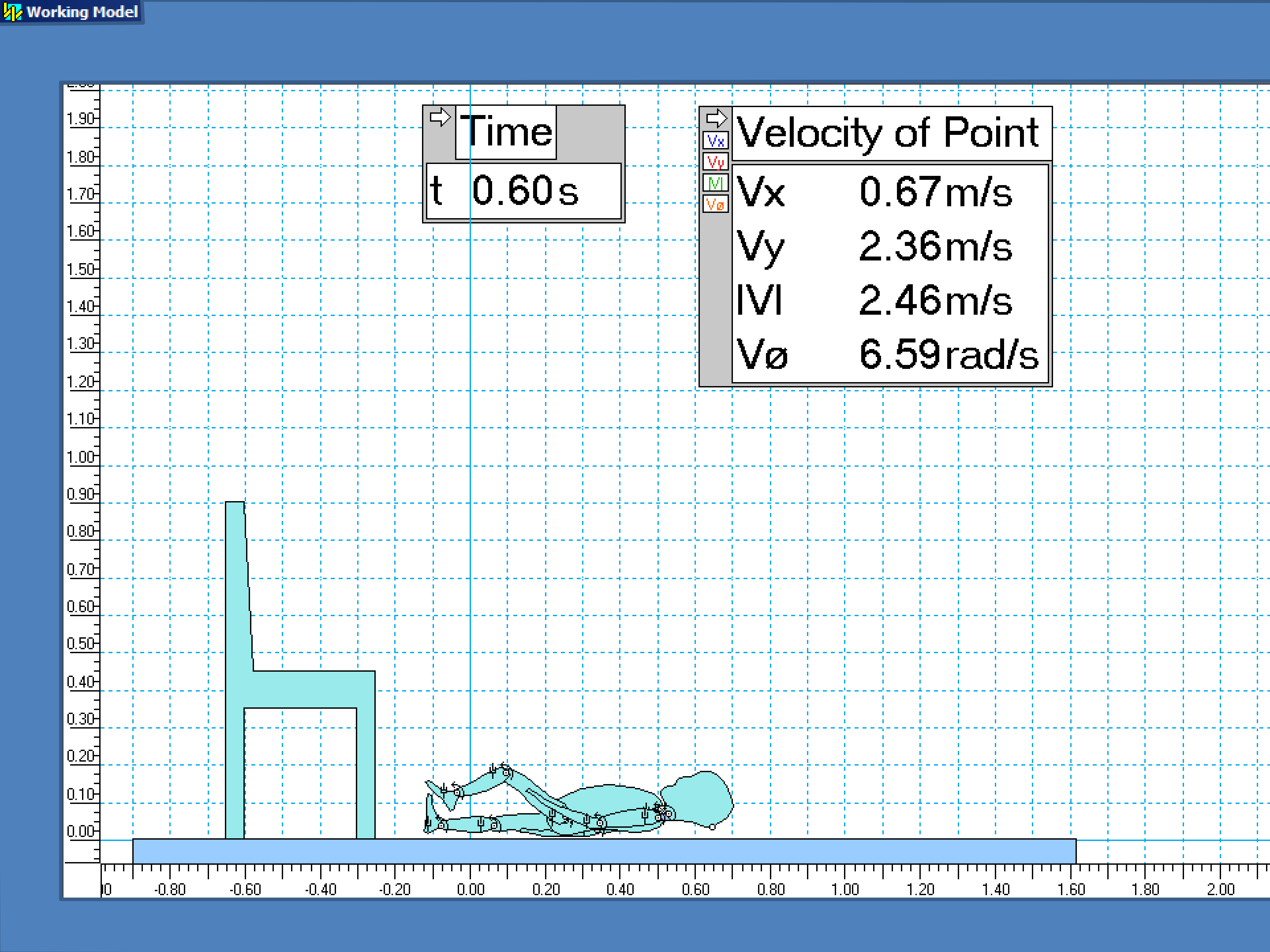
Rebound from the floor also produces extreme angular acceleration or a shaking effect of the head about the neck.

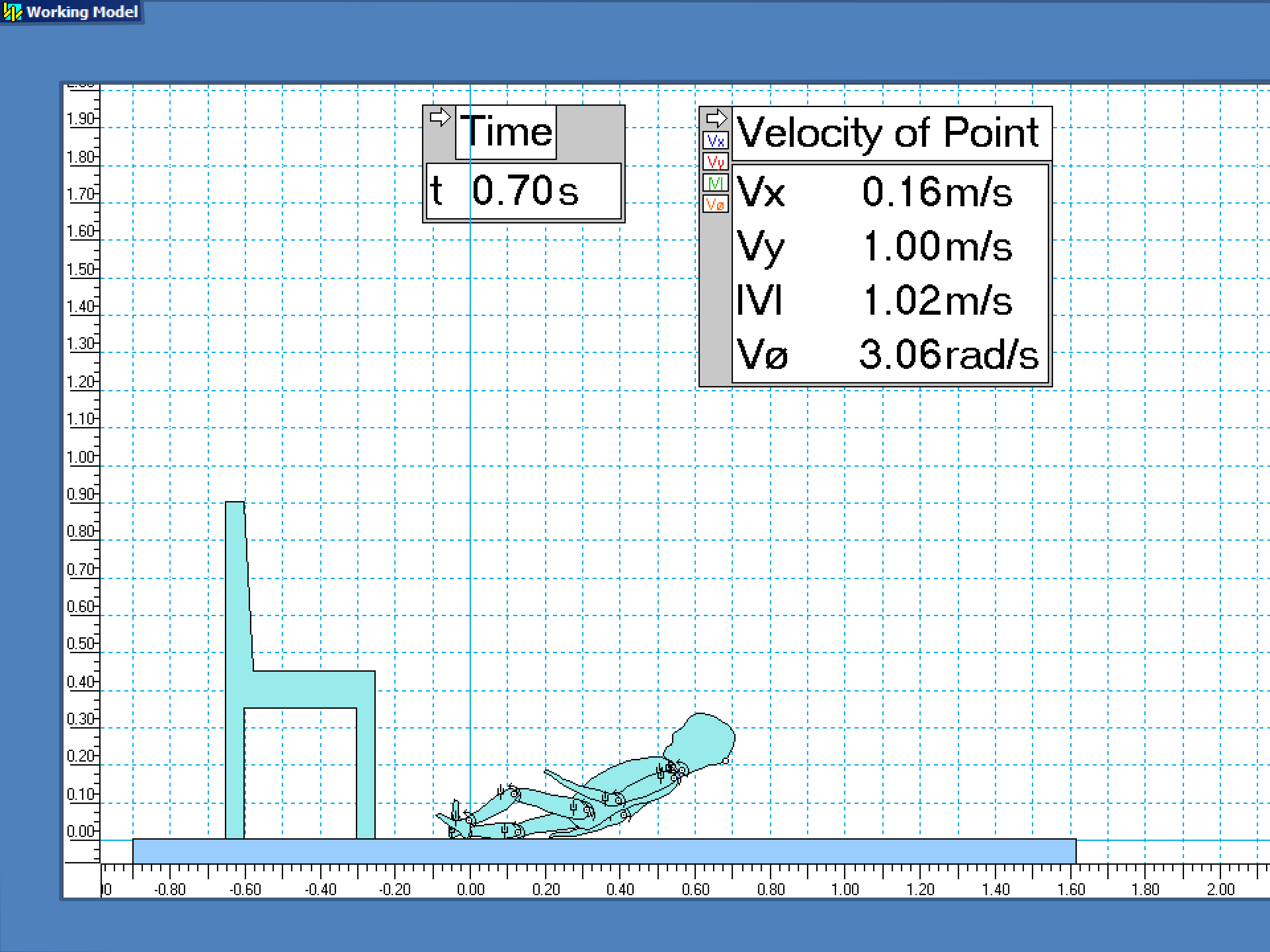
For contact time lasting 0.010 s,

Peak angular acceleration $a_{\emptyset} \approx 2\frac{\Delta V_{\emptyset}}{\Delta t}$

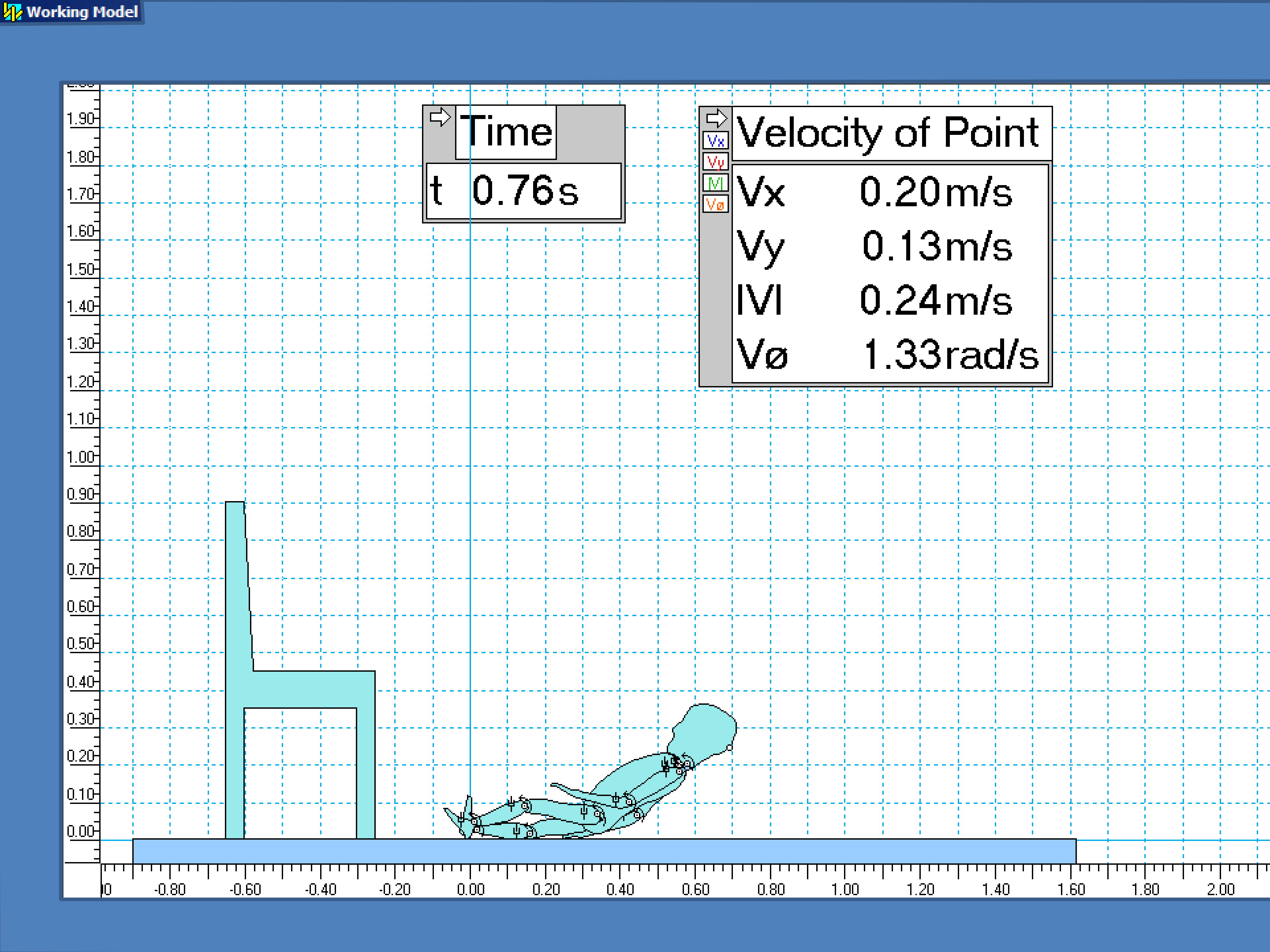
$\approx 9{,}800 \text{ rad}/s^2$

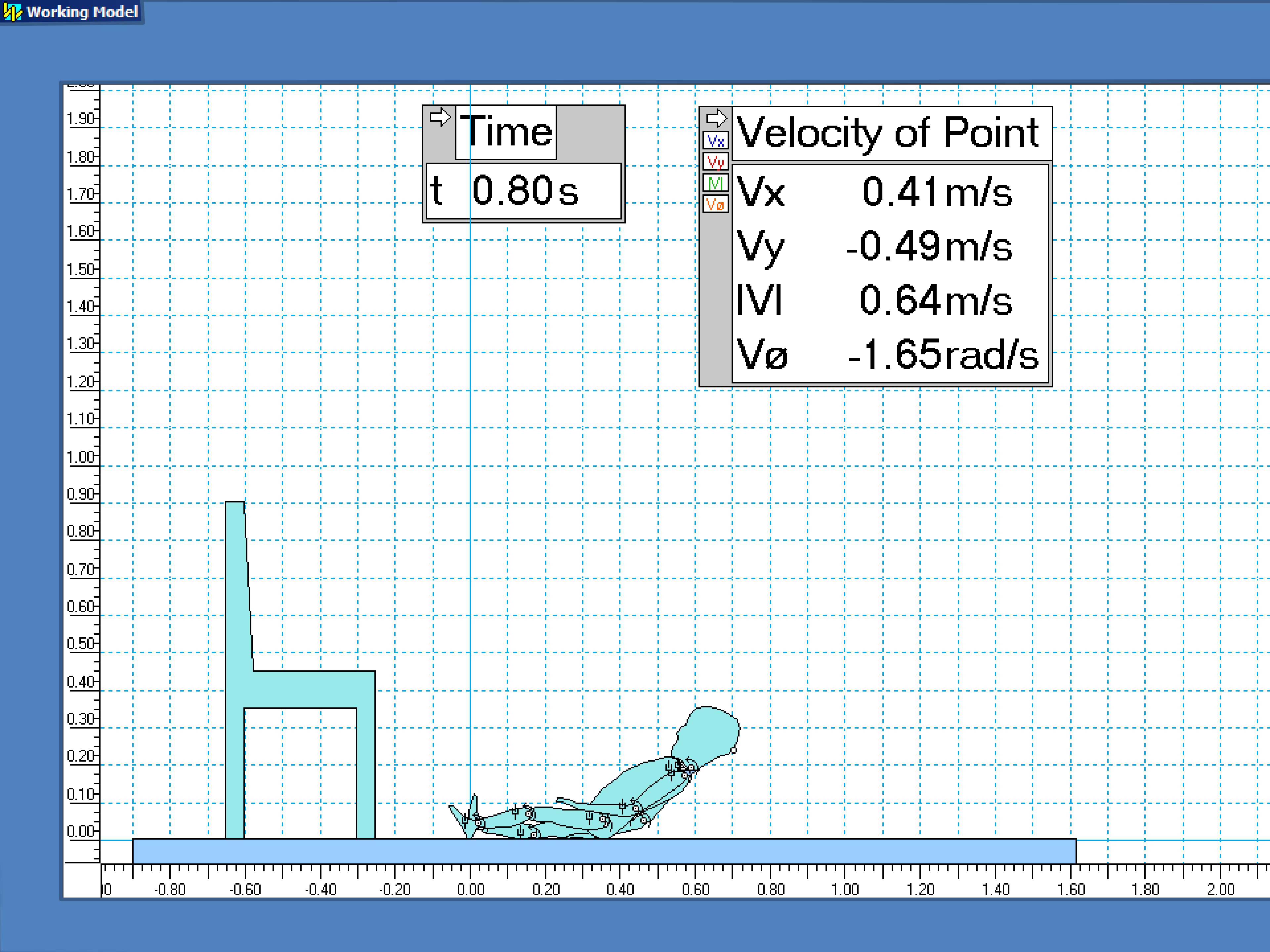
(Appendix A.)


Working Model
Time
t 0.60 s
Velocity of Point
Vx 0.67 m/s
Vy 2.36 m/s
|V| 2.46 m/s
Vø 6.59 rad/s
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00

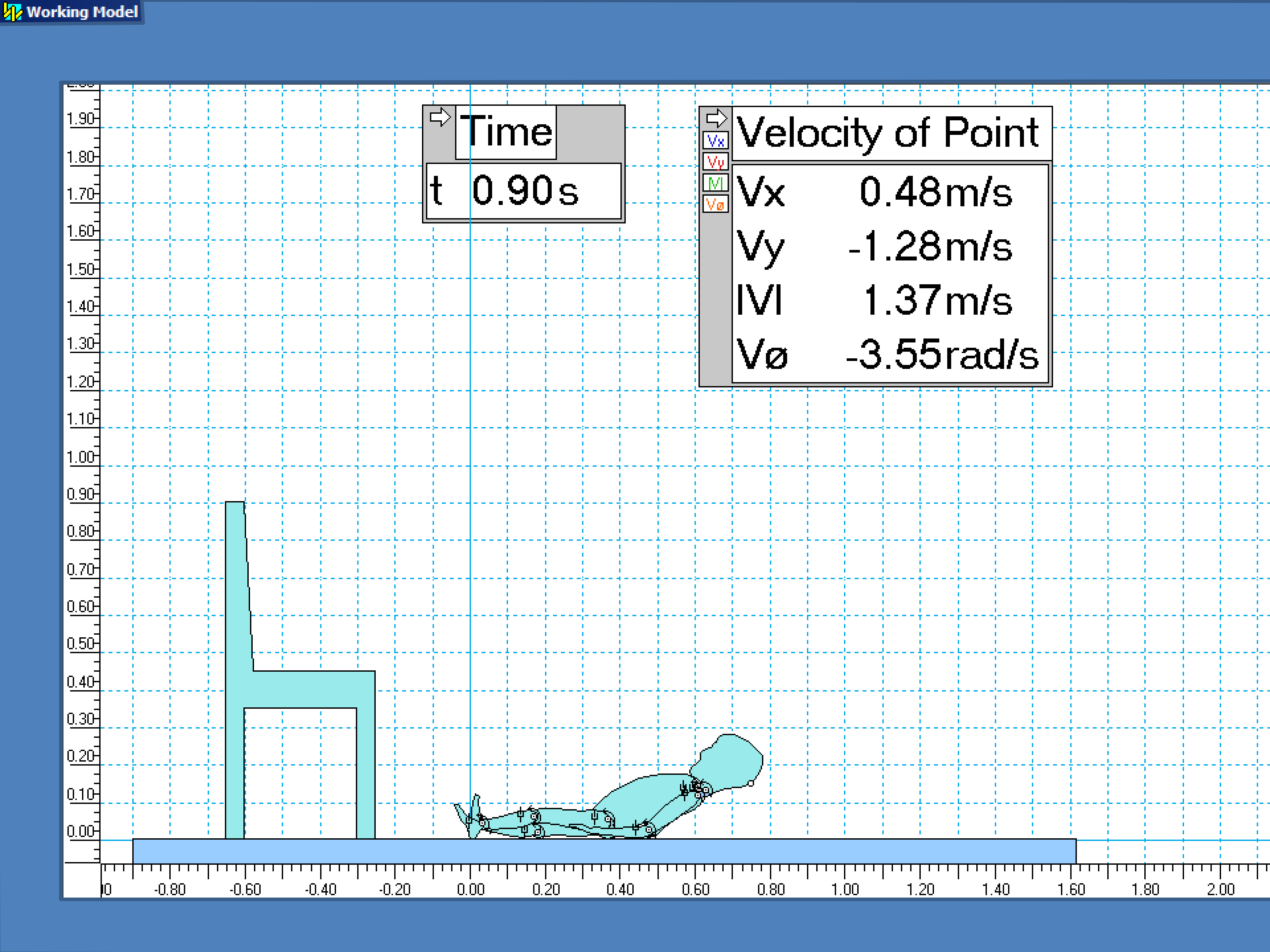


Working Model
Time
t 0.70s
Velocity of Point
Vx 0.16m/s
Vy 1.00m/s
|V| 1.02m/s
Vø 3.06rad/s
Vx
Vy
|V|
Vø
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00

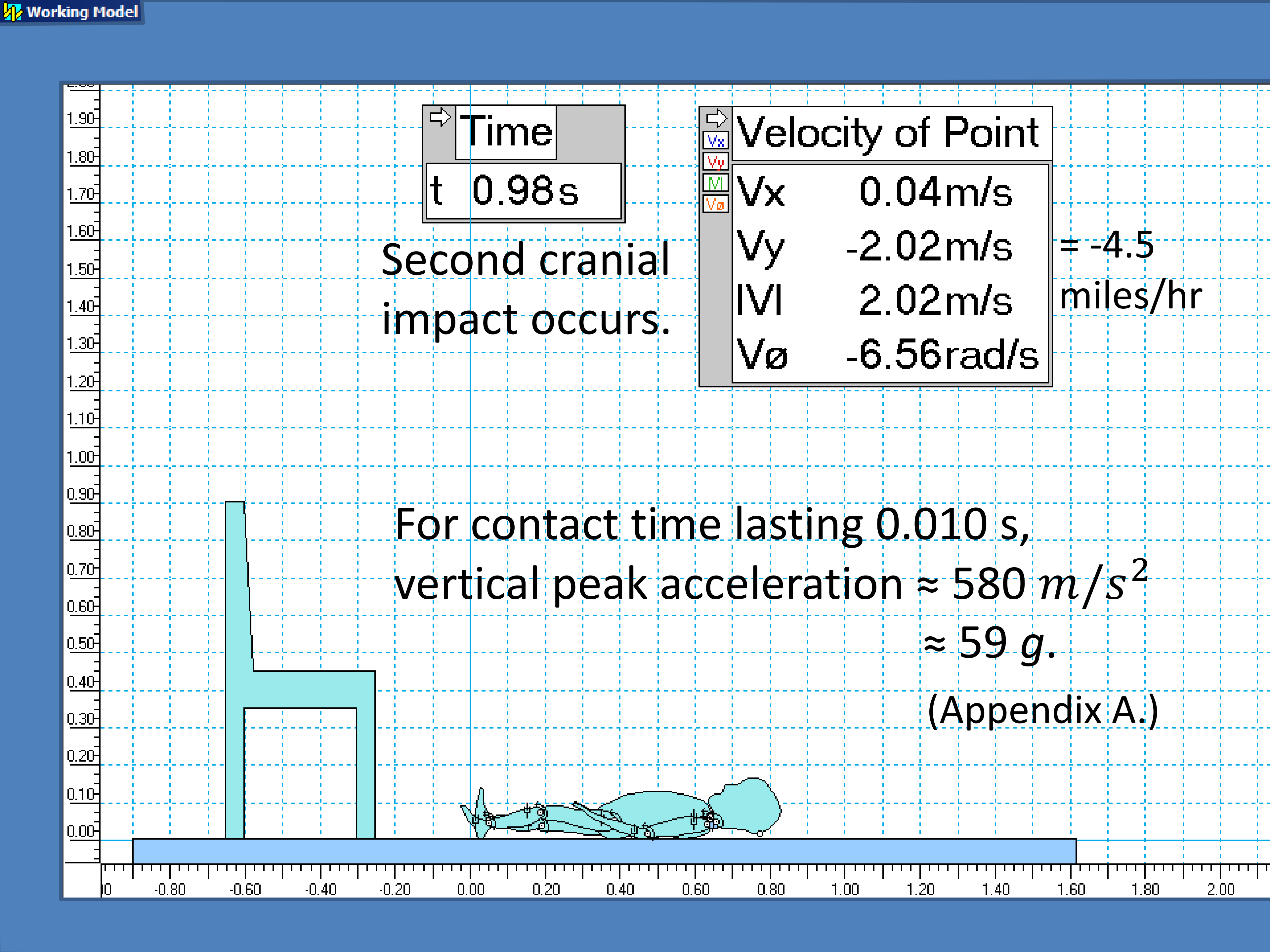

Working Model
Time
t 0.76s
Velocity of Point
Vx 0.20m/s
Vy 0.13m/s
|V| 0.24m/s
Vø 1.33rad/s
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00



Working Model
Time
t 0.80 s
Velocity of Point
Vx 0.41 m/s
Vy -0.49 m/s
|V| 0.64 m/s
Vø -1.65 rad/s



Working Model
Time
t 0.90 s
Velocity of Point
Vx 0.48 m/s
Vy -1.28 m/s
|V| 1.37 m/s
Vø -3.55 rad/s



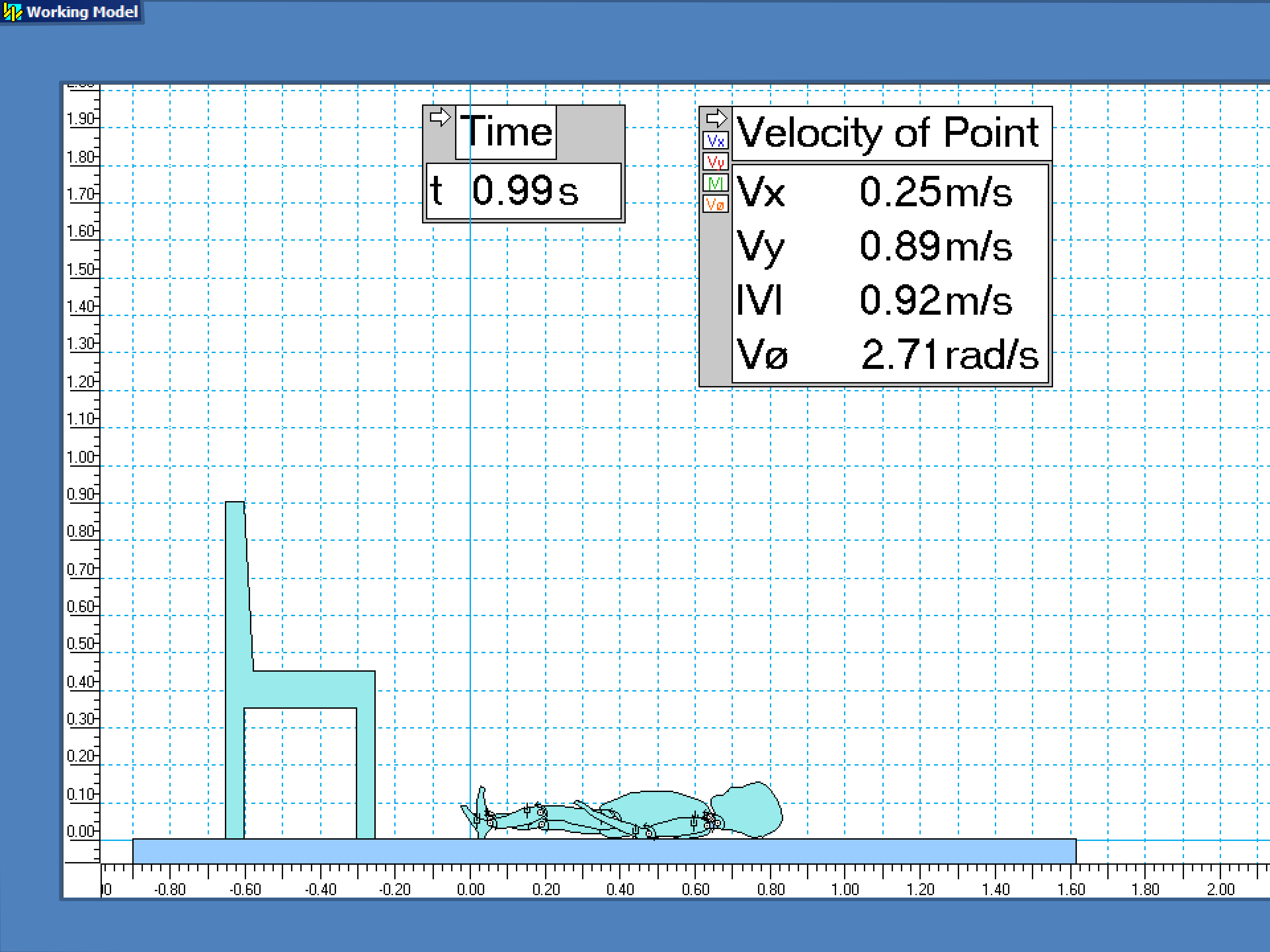
Second cranial impact occurs.

= -4.5 miles/hr

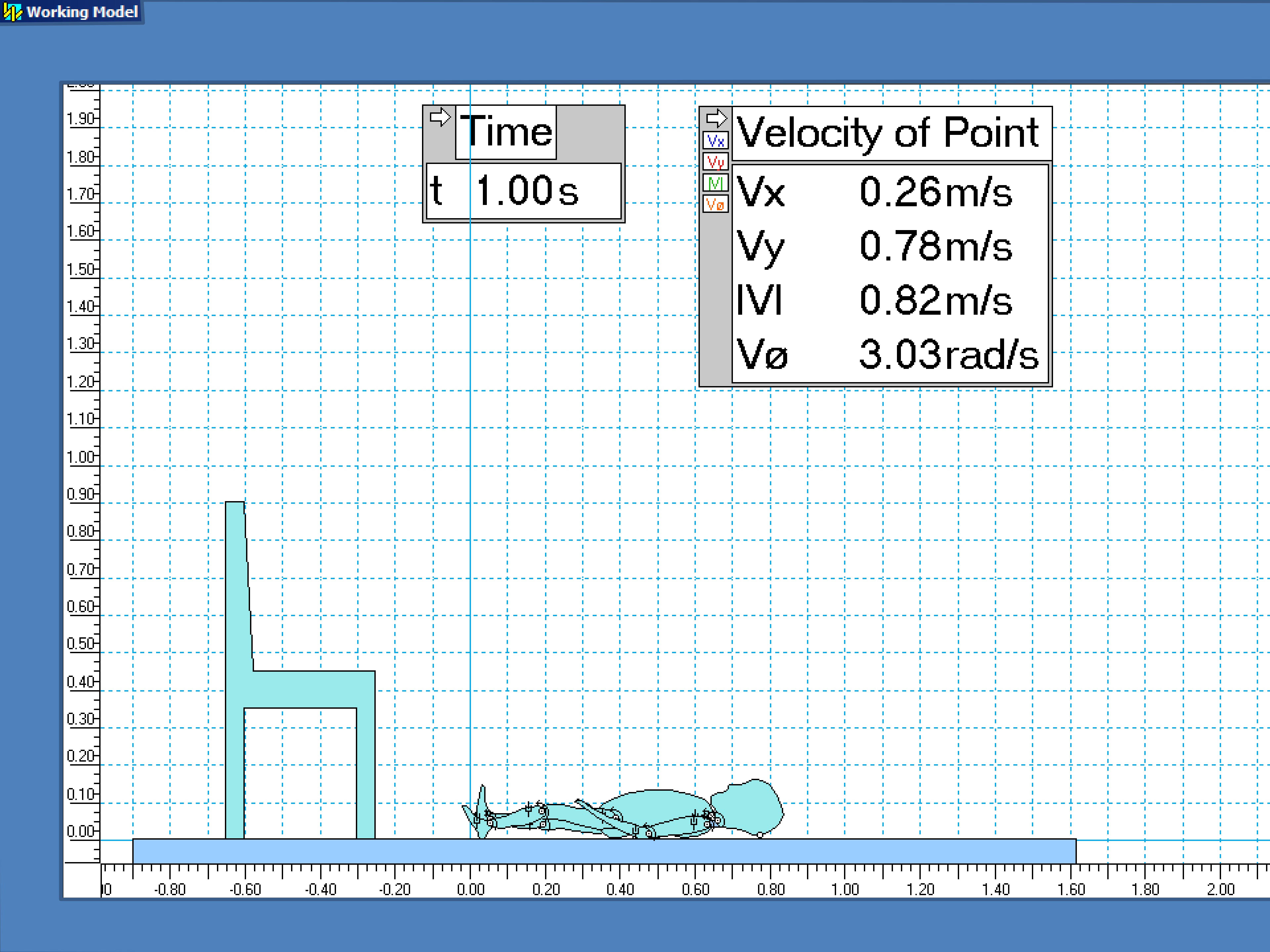
For contact time lasting 0.010 s, vertical peak acceleration ≈ 580 m/s^2

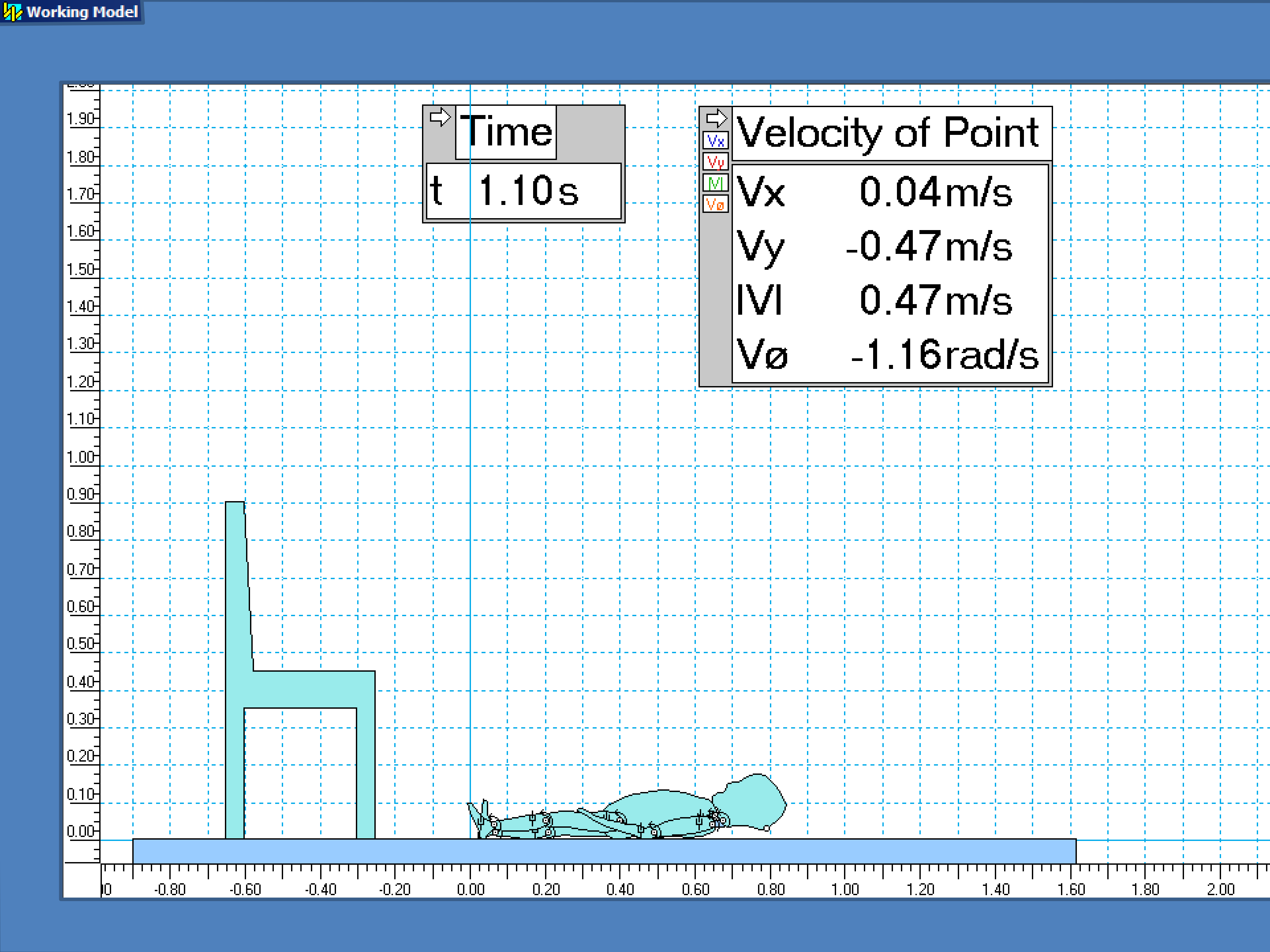
≈ 59 g.

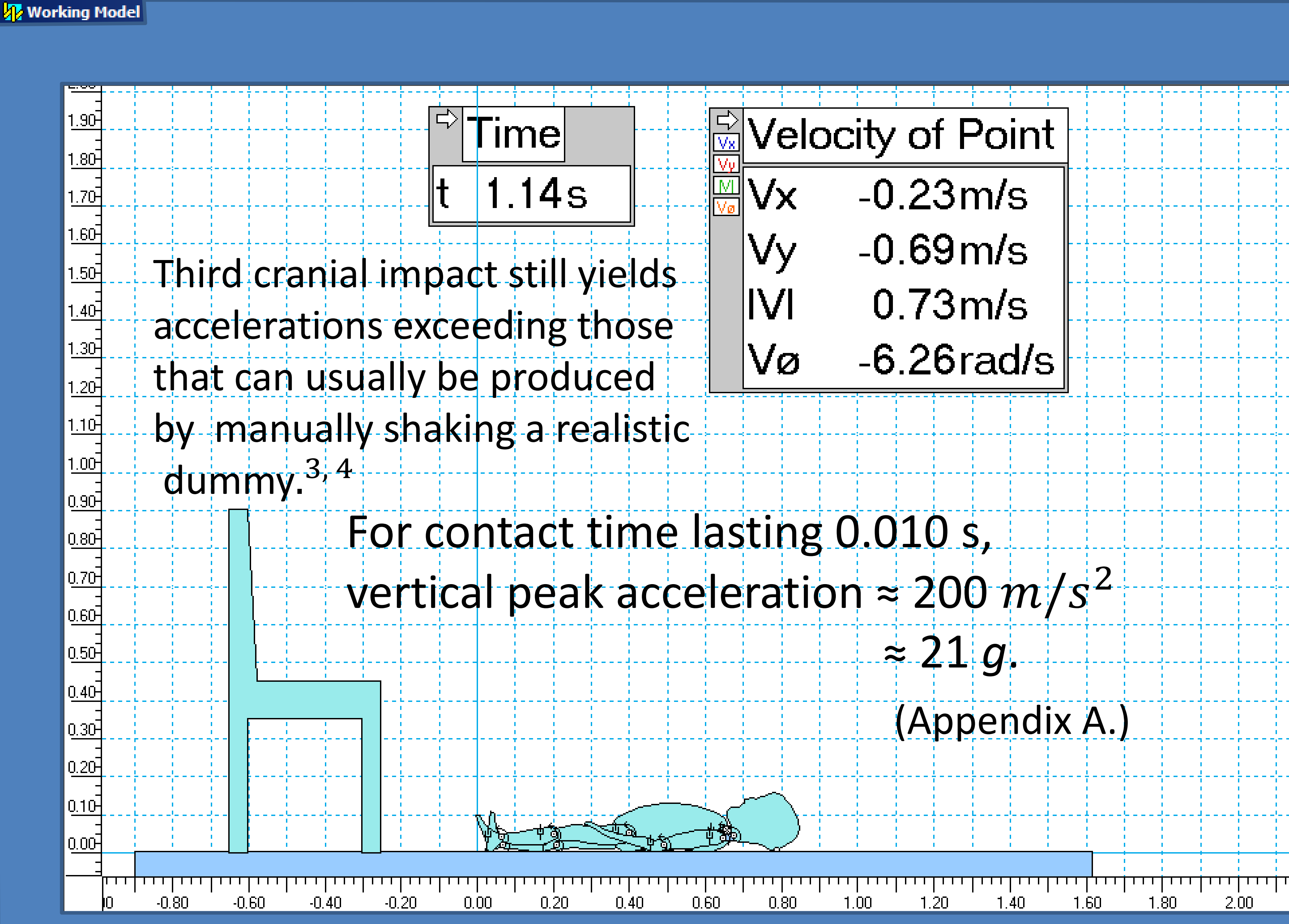
(Appendix A.)



Working Model
Time
t 0.99 s
Velocity of Point
Vx 0.25 m/s
Vy 0.89 m/s
|V| 0.92 m/s
Vø 2.71 rad/s


Working Model
Time
t 1.00s
Velocity of Point
Vx 0.26m/s
Vy 0.78m/s
|V| 0.82m/s
Vø 3.03rad/s


Working Model
Time
t 1.10s
Velocity of Point
Vx
Vy
M
Vø
Vx 0.04m/s
Vy -0.47m/s
lVl 0.47m/s
Vø -1.16rad/s
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.80
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00

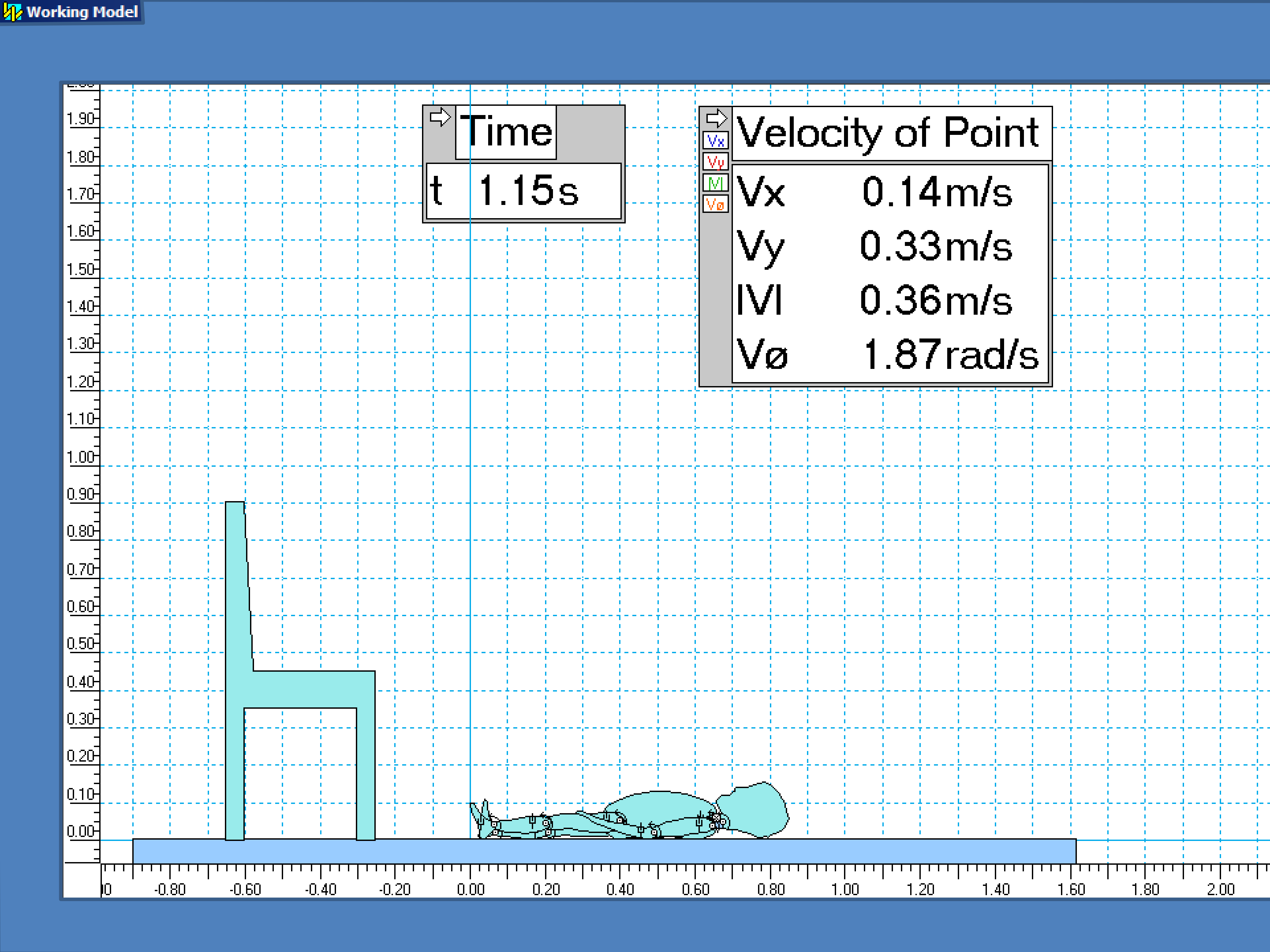


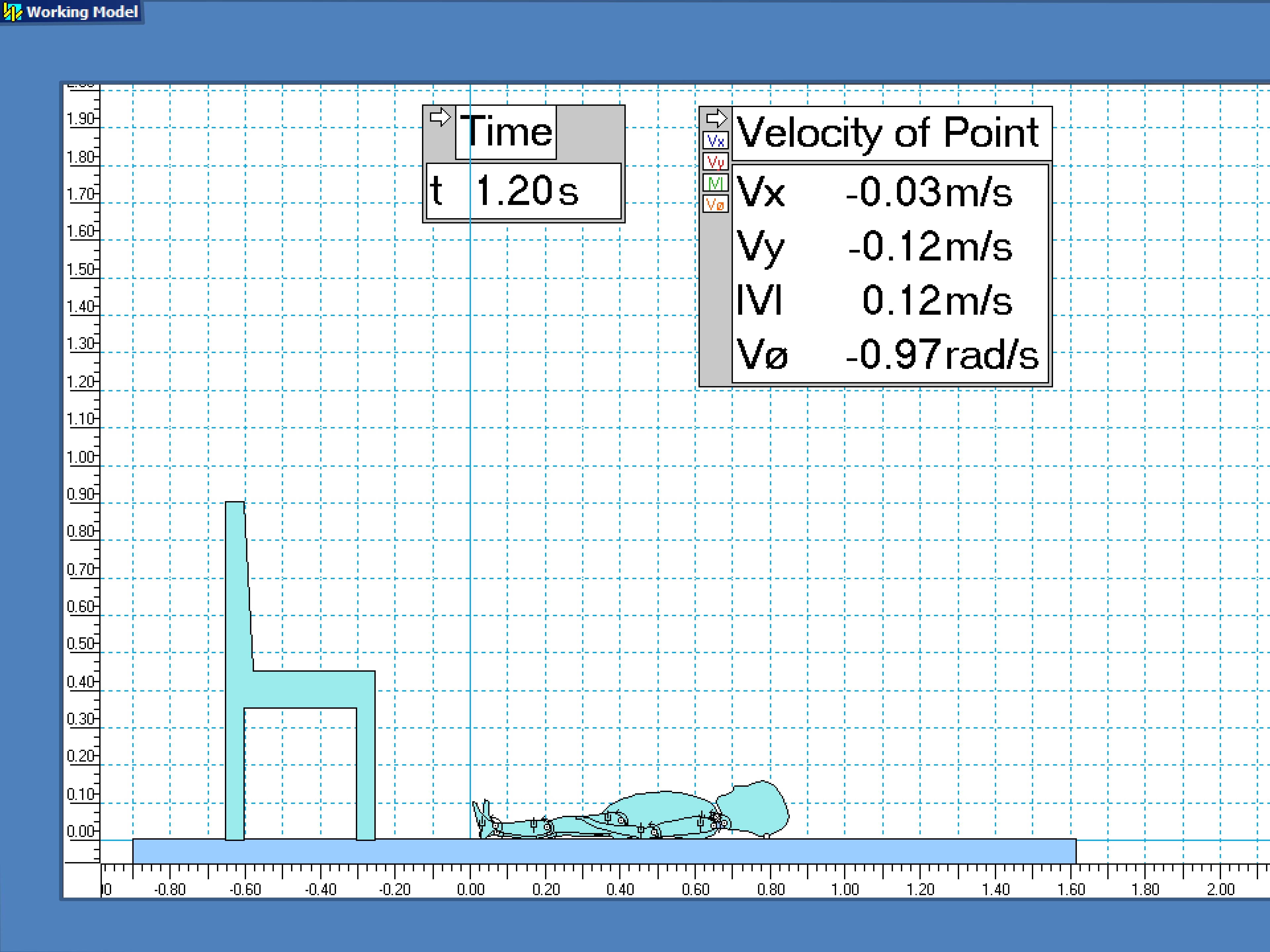
Third cranial impact still yields accelerations exceeding those that can usually be produced by manually shaking a realistic dummy.[3, 4]

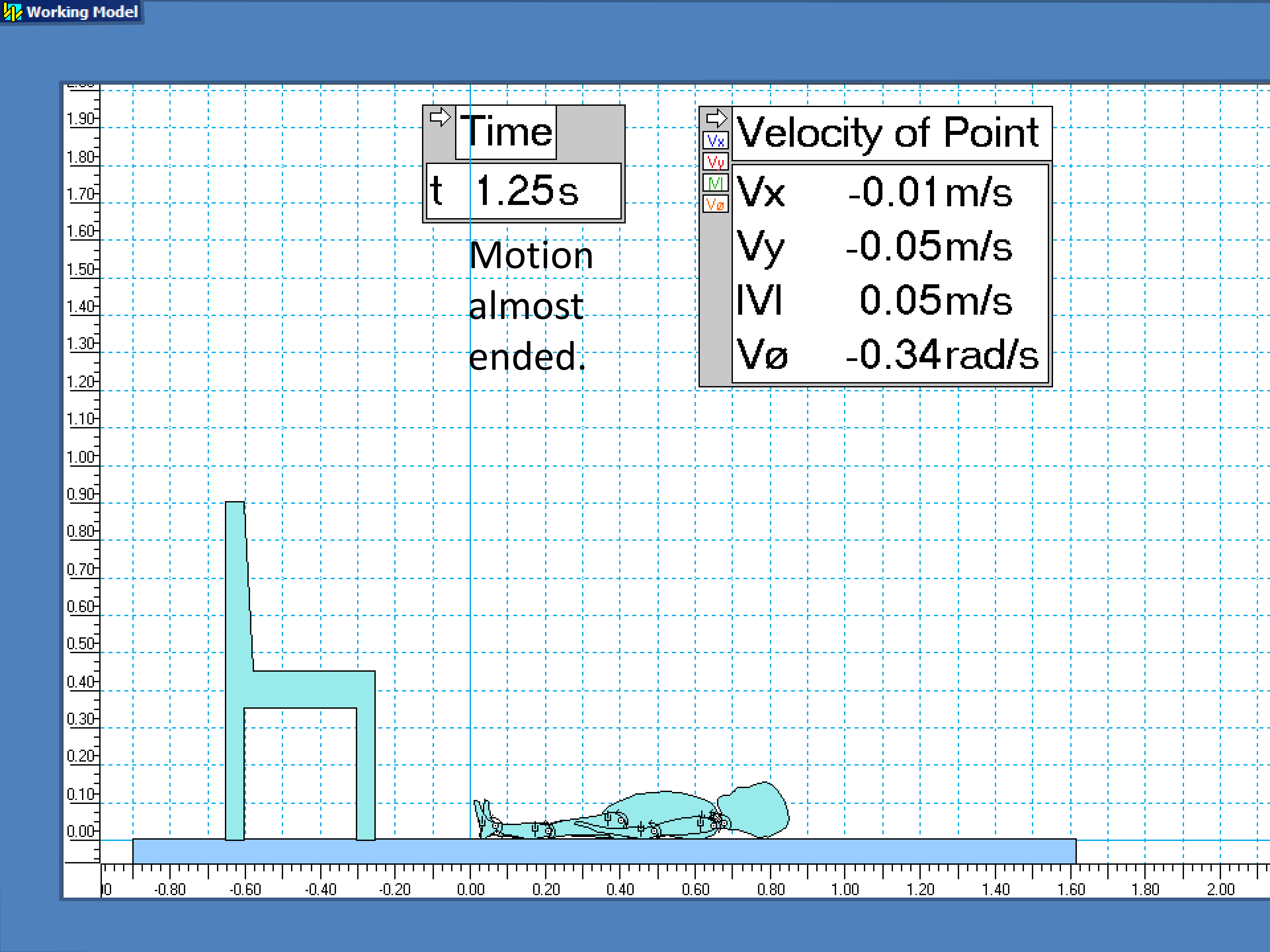
For contact time lasting 0.010 s, vertical peak acceleration $\approx 200\ m/s^2$

$\approx 21\ g.$

(Appendix A.)


Working Model
Time
t 1.15s
Velocity of Point
Vx 0.14m/s
Vy 0.33m/s
|V| 0.36m/s
Vø 1.87rad/s


Working Model
Time
t 1.20s
Velocity of Point
Vx -0.03m/s
Vy -0.12m/s
|V| 0.12m/s
Vø -0.97rad/s
1.90 1.80 1.70 1.60 1.50 1.40 1.30 1.20 1.10 1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
-0.80 -0.60 -0.40 -0.20 0.00 0.20 0.40 0.60 0.80 1.00 1.20 1.40 1.60 1.80 2.00


Working Model
Time
t 1.25s
Motion almost ended.
Velocity of Point
Vx -0.01m/s
Vy -0.05m/s
|V| 0.05m/s
Vø -0.34rad/s

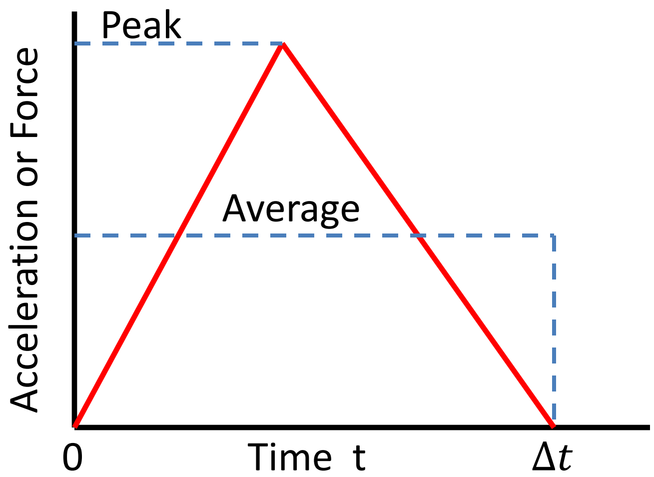
Conclusion

This simulation clearly shows the potential for severe head injuries from low-level falls. The resulting accelerations and forces for the first impact are more than 10 times greater than those that can usually be produced by manually shaking a realistic dummy.[3, 4]

Appendix A. Physics Relationships

- By definition, the average acceleration in the vertical dimension $\langle a_y \rangle \equiv \frac{\Delta v_y}{\Delta t}$, where Δv_y is the change in velocity and Δt is the interaction time with the floor.

- A toddler head colliding with a rigid surface has $\Delta t \approx 0.005\ s$.[3,4] Moderate padding extends this to $\Delta t \approx 0.020\ s$. $\Delta t = 0.010\ s$ was chosen as a typical value.



- As illustrated, a linear approximation of the acceleration or force between the floor and the head shows that the maximum or peak value is about twice the average.[4, 5]

- Divide accelerations in m/s^2 by $g = 9.8\ m/s^2$ to convert into *g's.* Multiply accelerations by mass to convert into forces.

Appendix B. Model Specifications

(typical 18 – month old toddler)[2]

Body Segment	Mass (kg)	Percent
Head	2.64	24.0
Neck	0.38	3.4
Torso	4.44	40.3
Combined upper arms	0.64	5.8
Combined lower arms with hands	0.64	5.8
Combined upper legs	1.13	10.3
Combined lower legs	0.91	8.3
Combined feet	0.23	2.1
TOTAL	11.0 kg	100%

Joint	Rotational damping (N-m-s/rad)*
Head-neck	0.06
Shoulders	0.13
Elbows	0.06
Front Hip Back Hip	0.50 1.00
Front Knee Back Knee	0.10 0.60
Ankles	0.32

*Rotational damping values chosen for realistic response since standards are impossible for a variable organism.

- By definition, elasticity or coefficient of restitution ≡ |rebound velocity / impact velocity|. The head, arms , feet and floor are assigned values of 0.5, while the other segments are 0.1 .

- All coefficients of friction = 0.30.

- Kutta-Merson with 0.001 second integration steps provides accuracy. Only about one step out of every hundred is illustrated.

References

1. Baker, Susan P., O'Neill, Brian, Ginsburg, Marvin J., and Li, Guohua. *The Injury Fact Book* (Oxford University Press 1992), 2nd ed., p.140

2. http://www.humaneticsatd.com/crash-test-dummies/children

3. Ommaya A K, Goldsmith W and Thibault L. Biomechanics and neuropathology of adult and paediatric head injury. British Journal of Neurosurgery 2002; 16(3): 220-242

4. Goldsmith W and Plunkett J. A biomechanical analysis of the causes of traumatic brain injury in infants and children. The American Journal of Forensic Medicine and Pathology June 2004; 25(2): 89-100

5. Cross, Rod. The Bounce of a Ball. American Journal of Physics March 1999; 67 (3): 222-227