Project Report: Reducing Shaker Injury

Project leader: Ken Shackel, Dept. of Pomology, UC Davis

Cooperating personnel: Hassan Abdel-Fattah, Tom Ferrari, Tom Rumsey

Objective:1) develop a mathematical analysis of shaker data, and 2) test whether the use of trunk pads increases the efficiency of power transfer between the shaker head and the tree trunk.

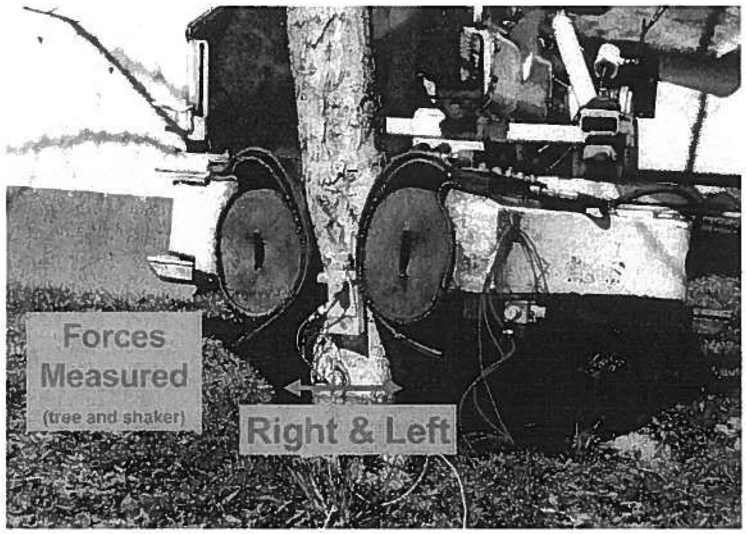
Background: In 2000, we documented that all of the commercial shakers tested caused a substantial up and down movement (averaging 27% of the side to side movement) in the almond tree during shaking. It is clear that this movement could damage the tree, both from the standpoint of bark damage and from the standpoint of root damage, but it is not clear how severe the damage might be under different orchard and harvest conditions, and whether or not there is a threshold for this damage. The analysis that we performed on the year 2000 data was sufficient to quantify acceleration and motion, both on the tree and on the shaker arm, but further analysis of this data was necessary for a solid statistical comparison of shakers. Recently, newly developed and patented plastic devices ("Trunk Pads") were introduced to the industry, and the claim was made that these pads will substantially increase the efficiency of power transfer, allowing a more efficient shake with less energy applied to the tree, which would benefit the industry. Additional tests with and without trunk pads were performed in 2001 for an evaluation of this effect.

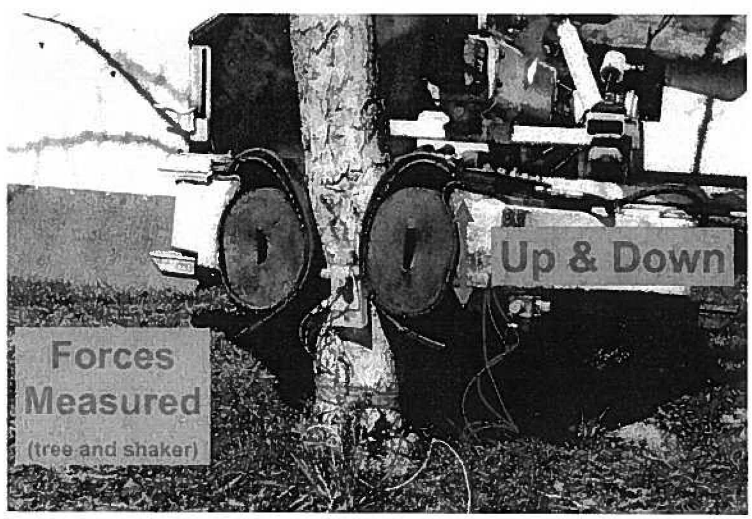
Procedures: A high speed data acquisition system for shock and vibration measurements was obtained on loan from the USDA post-harvest laboratory in Fresno, and two tri-axial accelerometer packages capable of withstanding shaking forces were fabricated at UCD. A number of field tests were performed using the commercially available harvesters indicated in Table 1.

Table 1. Shakers tested as part of this study (in alphabetical order).

AGH (American Grape Harvester)
Compton Enterprises
ENE (Erick Nielsen Enterprises, inc.)
FMC (Food Machinery Corporation)
OMC (Orchard Machinery Corporation)
Orchard-Rite

By agreement with the manufacturers, letters (A through F) were randomly assigned to each manufacturer to maintain confidentiality in the reporting of the test results. Each test consisted of at least two replicate 3 second shakes using a free wooden post in place of the tree (called a "free shake"), to determine the shaking forces in the absence of any tree influence. Acceleration was measured both on the shaker arm and on the post, and all three directions of movement were recorded and are labeled as the shaker operator would observe them while looking at the tree: "Right/Left" (perpendicular to the shaker arm), "In/Out" (parallel to the shaker arm), and "Up/Down" (see pictures to the right). For the shakers tested under orchard conditions, the free shake test was followed by one 3 second shake applied to each of five individual trees down a row, with accelerations measured on the shaker arm and on the tree. In all cases, the shakers were operated by experienced employees who were instructed to apply the same kind of shake as they normally would apply for the trees being harvested, with the exception that only 3 seconds of shaking would be given. In some cases, new harvesters were tested at the manufacturers shop in the free shake mode, but, as reported in 2000, there was no apparent difference between the way new and used shakers behaved, and hence all shakers will simply be summarize as individuals in this report.





Results and discussion:

A typical example of the g-forces and displacements recorded for a tree shake is shown in Figs. 4 and 5. A total of 19 individual shakers were tested using a free shake and 11 of these were tested under field conditions during almond harvest (Table 2). For the free shake, statistically significant differences between the shakers both in the absolute amount of displacement (Table 3) and in the displacement expressed relative to the displacement in the main direction of shaking (Right/Left) were found (Table 4).

Shaker "C" exhibited the lowest Up/Down displacement in both absolute and relative terms. A low absolute value of Up/Down displacement would be desirable from the standpoint of reducing shaker injury, but not desirable if it were associated with low overall shaker displacement, since displacement is necessary for effective fruit removal. In the case of shaker "C" however, both the Right/Left and In/Out displacements were in the upper range of those observed for all shakers tested. Hence, at least in a free shake, this shaker is applying substantial displacements in the desired plane of shaking without causing a substantial Up/Down displacement. As found previously, there was a substantial range in the Up/Down displacements exhibited by shakers, ranging from 6.9% to 45% of the displacements measured in the Right/Left direction (Table 4).

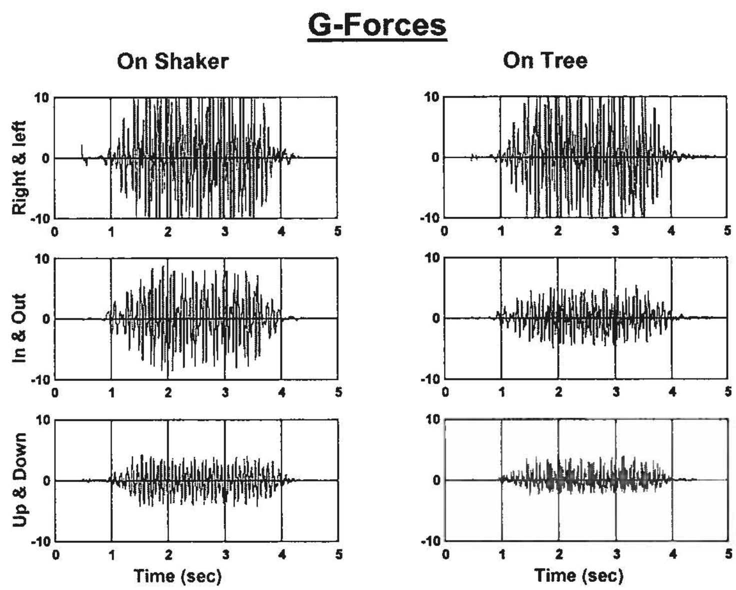


Figure 4. Example of g-forces recorded during a tree shake.

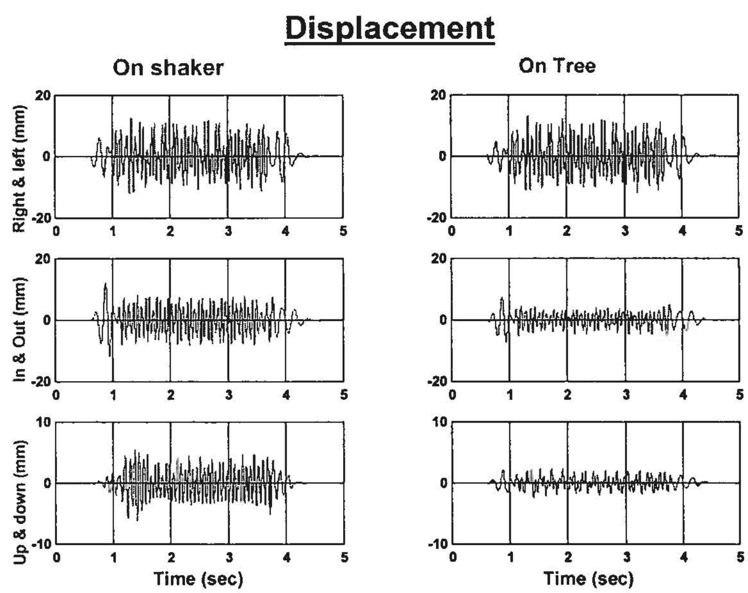


Figure 5. Example of displacements measured during a tree shake.

For orchard tests, shakers were compared based on the percent Right/Left value, in order to account for the influence of tree size on overall shaker displacement, and statistically significant differences were found between shakers, with the undesirable Up/Down displacement ranging from 11.2% to 34.2% (Table 5). A value of 33% in this analysis means that the tree is moving up and down one-third of the distance that it is moving right and left. Even though there was some statistical overlap among shakers, B4, A3 and E1 were all close to this 33% value, and were statistically higher than most of the other shakers tested. As reported in 2000, these values indicate that the tree itself is experiencing substantial forces that may be undesirable both from the point of barking injury and from the point of potential damage to the root system.

In view of the potential implications of the Up/Down displacement for bark and root damage, it is important to evaluate whether this displacement arises solely from the motion of the shaker, or as a consequence of both the shaker motion and the resistance of the tree to the forces applied by the shaker. There was a significant positive correlation between the percent Up/Down exhibited during the free shake and the percent Up/Down exhibited by the tree for the same shaker (Fig 6). This correlation indicates that shakers which showed the highest Up/Down motions in a free shake also tended to show the highest Up/Down motions on the tree, and the simplest explanation for this is that the shakers themselves are causing the motion in this direction. There were some shakers that showed substantial deviation from this general trend:

Table 2. Shaker designations (A through F indicate manufacturer) and notes on the condition of the equipment and tests performed.

Shaker Designation	Notes/Condition	Tests Performed	
		Free Shake	Almond Harvest
A1	New, test design	X	
A2	Used	X	
A3	Used	X	X
A4	New, test design	X	X
B1	Used	X	
B2	New	X	
B3	Used	X	X
B4	Used	X	X
B5	Prune Shaker, Used	X	
B6	Used	X	X
C	Prune Shaker, Used	X	
D1	New	X	
D2	Walnut Shaker, New	X	
D3	Used	X	X
D4	Used	X	X
E1	Used	X	X
E2	Used	X	X
E3	Used	X	X
F	Used	X	X

Table 3. Average displacements measured on all shakers in each of the three shaking directions, during a "free shake" test. For each direction, the displacements in millimeters are ranked from high to low. The manufacturer/shaker column identifies each individual shaker tested, with capital letters A through F indicating the manufacturer. Small letters following the displacement values indicate statistical significance at the 5% level of DNMRT. Any displacements that share a common small letter are not considered significantly different.

Right/Left direction		In/Out direction		Up/Down direction	
Mfg/Shaker	Displacement (mm)	Mfg/Shaker	Displacement (mm)	Mfg/Shaker	Displacement (mm)
A4	29.3 a	B5	12.2 a	A4	5.6 a
D2	14.2 b	D2	11.0 b	D2	5.5 a
C	13.7 bc	B4	8.8 c	B4	4.0 b
B5	13.6 bc	B2	8.8 c	B3	3.7 b
F	13.1 bcd	B3	8.4 c	A1	3.6 b
E3	12.4 cd	C	8.2 c	A3	3.3 bc
A1	12.1 d	D1	7.1 d	A2	3.1 bcd
E1	10.7 e	E3	7.0 d	B6	2.4 cde
B3	10.3 ef	A2	6.9 d	B2	2.3 cde
B4	10.2 ef	E2	6.6 def	D1	2.1 de
D1	10.1 ef	A3	6.5 def	D3	2.1 de
B2	9.5 efg	B6	6.4 def	E3	2.0 ef
E2	9.3 efg	F	6.2 defg	B5	2.0 ef
D4	9.0 fgh	E1	6.2 defg	D4	2.0 ef
D3	8.9 fgh	D4	5.9 efg	E1	1.7 ef
A2	8.0 ghi	D3	5.8 fg	B1	1.7 ef
B6	7.8 hi	B1	5.5 g	F	1.7 ef
B1	7.3 i	A4	3.5 h	E2	1.4 ef
A3	7.2 i	A1	1.9 i	C	0.9 f

Table 4. Displacements from Table 3 measured in the In/Out and Up/Down direction, expressed as a percent of the displacement in the main direction of shaking (Right/Left).

In/Out direction		Up/Down direction	
Mfg/Shaker	Displacement as % of Right/Left	Mfg/Shaker	Displacement as % of Right/Left
B2	92.4% a	A3	45.0% a
A3	90.7% a	D2	40.2% ab
B5	90.6% a	B4	39.3% ab
A2	87.5% ab	A2	37.8% ab
B4	86.7% ab	B3	35.3% ab
B6	82.7% ab	B6	31.3% bc
B3	81.5% abc	A1	30.0% bc
D2	77.8% abc	D3	24.1% cd
B1	75.5% abcd	B2	24.0% cd
E2	71.9% bcde	D1	23.1% cde
D1	70.9% bcde	B1	23.0% cde
D4	65.6% cde	D4	21.7% cde
D3	65.0% cde	A4	19.0% de
E1	60.4% def	E3	17.2% de
C	59.7% def	E1	16.0% def
E3	58.6% ef	E2	14.4% def
F	47.9% f	B5	14.4% def
A1	15.6% g	F	12.8% ef
A4	12.1% g	C	6.9% f

Table 5. Displacements measured during tree shaking in the In/Out and Up/Down direction, expressed as a percent of the displacement in the main direction of shaking (Right/Left).

In/Out direction		Up/Down direction	
Mfg/Shaker	Displacement as % of Right/Left	Mfg/Shaker	Displacement as % of Right/Left
B4	108.0% a	B4	34.2% a
B3	93.6% b	A3	32.9% ab
A3	93.1% b	E1	28.2% ab
B6	55.8% c	B3	23.5% bc
E1	52.7% cd	D4	17.7% cd
D4	49.0% cd	A4	16.1% cd
E3	48.2% cde	E2	14.8% cd
E2	38.9% de	E3	14.7% cd
D3	38.9% de	F	13.9% cd
F	33.1% e	B6	13.8% cd
A4	16.9% f	D3	11.2% d

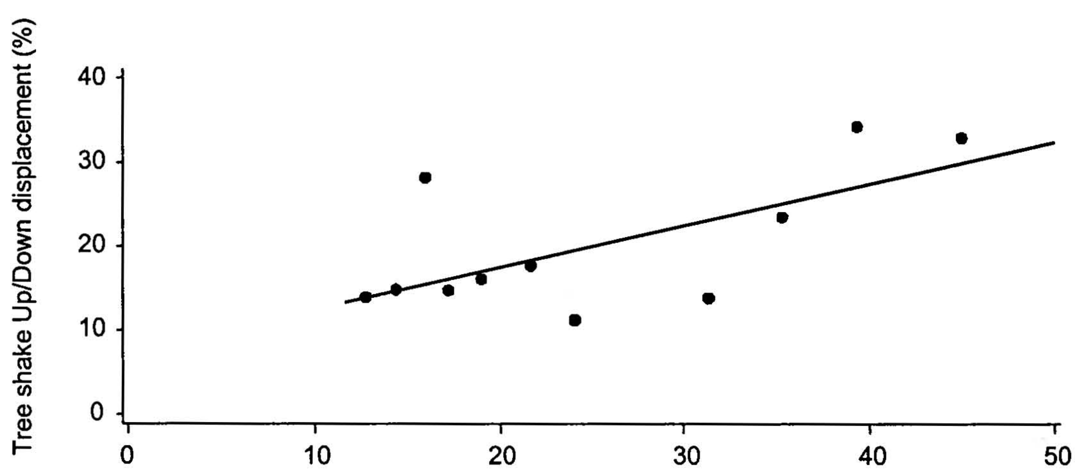


Figure 6. Relation of the Up/Down displacement (as a percent of Right/Left) observed on the tree during a tree shake to that observed on the shaker during a free shake for each individual shaker tested. Each point is an average of at least two free shake determinations and typically five tree shakes. The line is the best fit regression (equation: $Y = 0.08 + 0.49*X$, $r^2 = 0.43*$).

two (D3, B6) showing the lowest values of Up/Down tree movement despite moderate values of this movement in the free shake, and one (E1) showing a relatively high value of Up/Down tree movement despite a low value of this movement in the free shake (Fig. 6). This may indicate that the tree can play some role in the size of the Up/Down displacements experienced during shaking, but further research will be required to determine the relative importance of this effect. The general trend across shakers however (Fig. 6) indicates that the Up/Down tree movement during shaking is a result of Up/Down forces being applied by the shaker.

One important aspect of shaking that the tree clearly influenced was the shaker pattern. By combining the data of Right/Left and In/Out displacement, it was possible to reconstruct this pattern, and three examples are shown in Fig. 7. One test design shaker (A4) was found to have very little In/Out movement compared to Right/Left movement during a free shake, but this shaker exhibited a significant increase in the In/Out movement when shaking a tree, particularly on the shaker arm (Fig. 7). In contrast to this, the free shake patterns of shakers E3 and D4, which were multidirectional in the free shake, became predominantly diagonal on the shaker and

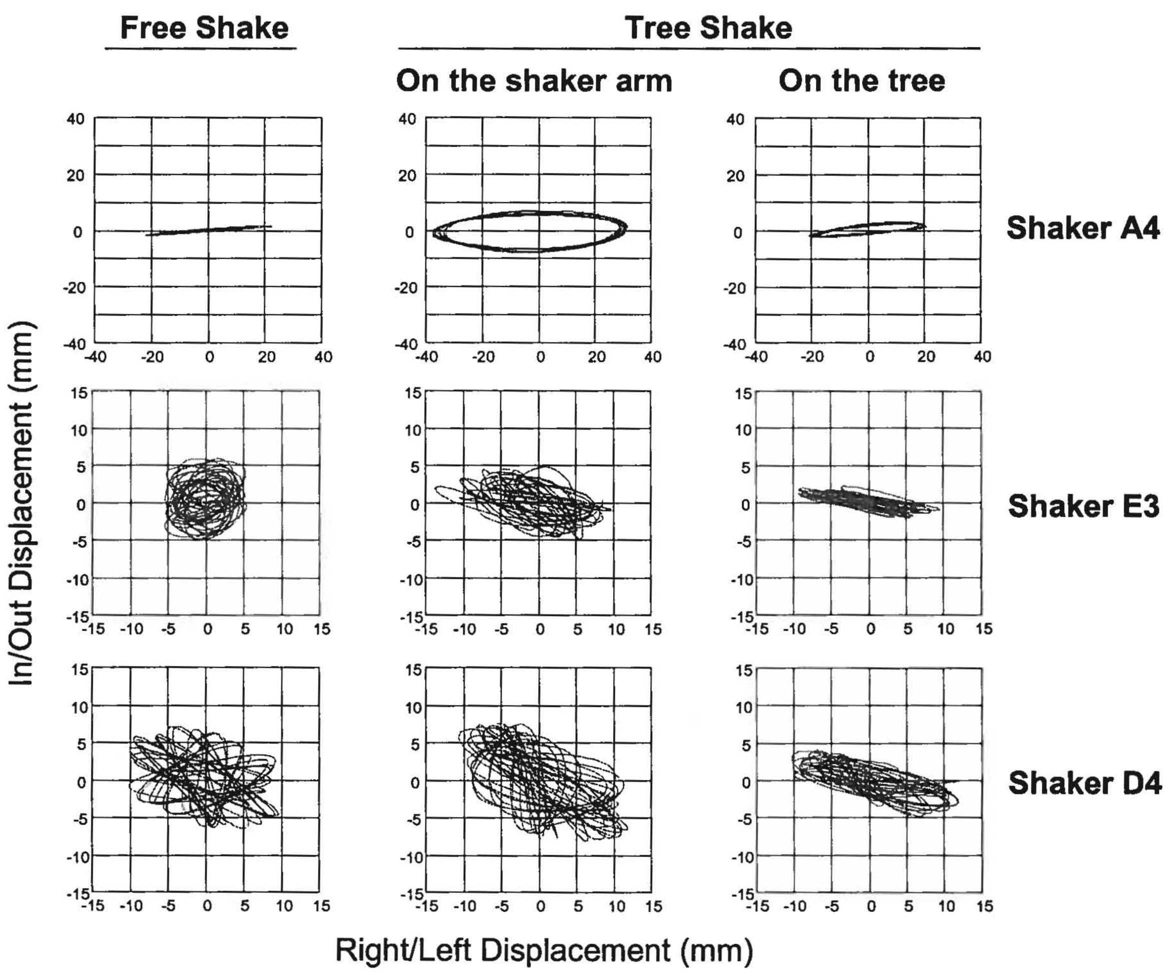


Figure 7. Examples of shaker patterns recorded on three individual shakers during a free shake, and for the same shakers during a tree shake. For the tree shake, patterns were recorded both on the shaker arm and on the tree.

predominantly Right/Left on the tree during a tree shake (Fig 7). These patterns clearly demonstrate that the tree has an important influence on the motion of the shaker, and that the tree may exhibit a shaking pattern that is quite different from the pattern that the shaker is designed to produce. If the shaking pattern on the tree is an important factor to consider in shaker design, then there may be a need to develop more detained information on how the tree and shaker interact during shaking.

The use of plastic "Trunk Pads" (Fig. 8) anchored into the tree trunk, has been suggested as a means of reducing shaker injury in almonds and other mechanically harvested crops, and it is clear that any device which prevents the direct contact between the shaker pads and the tree bark should reduce the risk of barking injury in almonds. It has further been suggested however, that because "Trunk Pads" are anchored into the wood of the tree, the transmission of force between the shaker and the tree should be more efficient. We tested this hypothesis using two shakers (B6 and E3), but found no evidence of any difference in the tree displacement in any direction with and without the use of "Trunk Pads" (Table 6). In the In/Out direction there was always a slight reduction in the displacement associated with the use of "Trunk Pads," which is opposite to that expected for a more efficient transfer of power, but interestingly, in the Up/Down direction there was always an increase in displacement. If the Up/Down tree displacement is associated with damage to the root system, then it may be prudent to consider this aspect of tree damage, in addition to the evaluation of barking injury, when evaluating the overall effects of using "Trunk Pads."

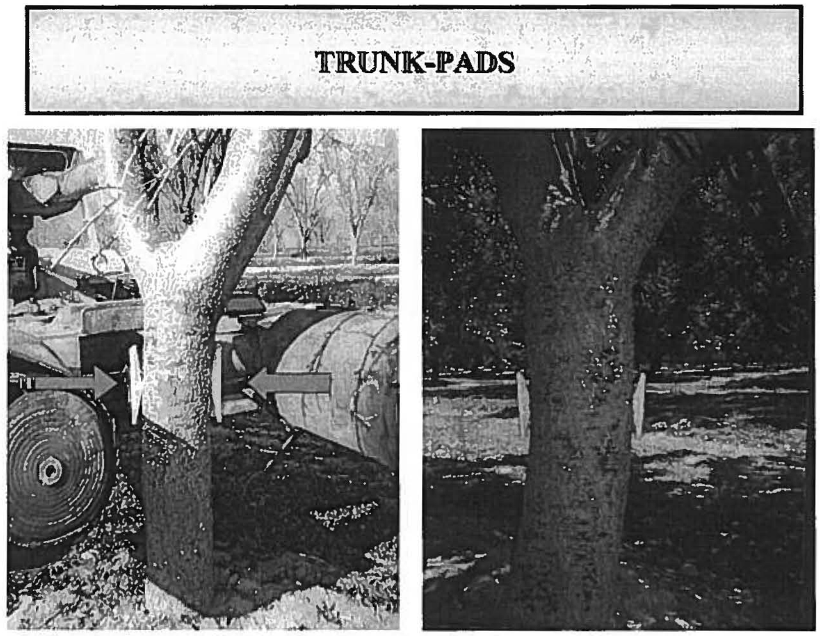


Figure 8.

Table 6. Effect on displacements experienced by the tree with and without the use of "Trunk Pads." Each value is the average of 5 individual tree replicates. There were no statistically significant effects of the pads.

Mfg/Shaker	Right/Left displacement (mm)	In/Out displacement (mm) and as % of Right/Left	Up/Down displacement (mm) and as % of Right/Left
B6	8.9	4.9 (56%)	1.2 (14%)
B6 + "Trunk Pads"	9.4	4.4 (47%)	1.6 (17%)
E3	9.2	4.4 (48%)	1.3 (15%)
E3 + "Trunk Pads"	8.0	3.4 (42%)	1.9 (24%)

Conclusions: Our analysis of a number of almond shakers under field conditions confirms earlier findings that most commercial shakers cause a substantial Up/Down displacement in the tree during shaking, that this displacement is largely due to the shaker itself, but that some commercial shakers have significantly lower Up/Down displacements than others. Hence there appears to be substantial room for reducing this undesirable motion under commercial conditions. We have also determined that the pattern of shaking experienced by the tree may be considerably different from that applied by the shaker, and that further work may be necessary to develop more information about how the shaker and tree interact. There was no statistically significant effect of the use of "Trunk Pads" on tree displacement during shaking, although a small but consistently higher Up/Down displacement with "Trunk Pads" indicates that root system health should be one of the considerations used when evaluating the possible benefits of this approach to reducing barking injury.