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Use of an Impact Recording Device to Determine the Risk of Bruising in Packaged Potatoes

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Abstract

Handling potatoes individually or collectively in packages can create opportunities for potatoes to develop quality defects including blackspot and shatter bruise. Three trials were conducted to examine how handling packaged potatoes can influence the risk for physical damage including shatter and blackspot bruise. An impact recording device was used to record peak acceleration (max g-force) in common fresh market packaging options (boxes or bales) at four drop heights (15 to 91 cm) on to three different surface types. When boxed potatoes were dropped onto concrete or a plastic slip, the potatoes on the bottom of the box had the highest risk of damage (greater than 100 g-force). When drop heights were lowered, or when cushioning material was added to hard surfaces (e.g., wooden pallet on top of concrete floor), the risk for impact damage was decreased throughout the box. When palletizing boxed potatoes, the risk of bruise decreased after the first layer was stacked on the pallet. Drop heights need to be below 15 cm, especially when making the first layer in a palletized stack of packaged potatoes to reduce potential bruising. The risk of high peak accelerations was not seen in the dropped or stationary bales for any of the drop heights examined. This study provided information for educating personnel on handling packaged potatoes and determining situations in which robotic stacking equipment needs to be adjusted to lower drop heights of packaged potatoes.

Keywords Drops · Handling · Shipments · IRD · Packing · Bruise

Introduction

U.S. potato yields increased by 8,535 kg per acre between 1981 and 2021 (USDA 2019, 2022). This increase in production has demanded the ability to handle a greater volume of potatoes in the same timeframe each year. To meet this demand, harvesting and handling operations have become more reliant on machinery and automation rather than manual labor to efficiently harvest, wash, sort, package, and transport potatoes. At each point potatoes are handled in post-harvest operations it is crucial to minimize quality losses due to bruising. These quality losses can be associated with rejections or downgrades by retailers that can lead to a loss in profitability. Bruises occur because of major and minor physical impacts when tubers contact equipment components, change direction, or drop from conveyor belts onto different surfaces (Bentini et al. 2006; Hyde et al. 1988).

One way to minimize bruise is to monitor equipment during harvest and handling operations in areas of high bruise probability where potatoes are moving. A tool used for assessing bruise potential during handling is an impact recording device (IRD; Praeger et al. 2013). IRDs have been used in a range of commodities concerned with impact related injuries such as apples, citrus fruit, tomatoes, bell peppers, and potatoes (Pason et al. 1990; Pothula et al. 2018; Manetto et al. 2017; Sargent et al. 1992). IRDs can record peak acceleration, velocity change, number of impacts endured, and provide a time stamp for each data point, although not all models include velocity change (Hollingshead et al. 2020). An IRD does not consider bruise susceptibility of the individual tuber, but rather measures

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the potential impact force a potato will encounter as it is handled. Hyde et al. (1992) reported that bruise potential of potato tubers was high when peak acceleration was above 100 g, and peak accelerations over 375 g would likely cause visible damage. These threshold values (100 to 375 g) are used throughout this study to help determine the risk of bruising associated with impact heights, packaging materials and impact force. Change in velocity (m/s) is calculated based on the area under the acceleration curve versus time, and accounts for the surface type tubers are dropped on and magnitude of impact (Hollingshead et al. 2020; Rady and Soliman 2015; Molema et al. 2000). The acceleration curve (Fig. 1, adapted from Molema et al. 2000) is an example of how the change in velocity and peak acceleration contributes to impact force. Collectively, these measurements can identify areas of the handling operation that have a risk for bruising.

Mass of an object, drop height, and type of surface at the impact point are the major components involved in determining peak acceleration and the velocity change experienced at time of impact (Deng et al. 2020; Thomson and Lopresti 2018). Drop height and impact surface type can be modified in a handling operation to lower the impact force. Decreasing drop heights as tubers transition from one surface to another can minimize damage throughout post-harvest equipment, while cushioning impact surfaces allows for greater drop heights before physical damage occurs. Using the two methods in unison can reduce the potential for impact damage. Rady and Soliman (2015) conducted drop tests with individual potatoes and IRD measurements and found drop heights exceeding 15 cm onto steel surfaces caused damage, but after affixing a rubber coating to the steel surface, drop heights could be increased to 25 cm before causing damage. In addition, tubers could be dropped up to 90 cm onto a layer of other tubers before damage occurred. Cushioning alters the change in velocity of the object.

Potatoes are typically unloaded at a packing facility to be washed, sorted, and packaged into various bag sizes or into bulk boxes or containers. The numerous handling steps prior to shipment can cause further physical damage in addition to damage sustained at harvest. Many bruise reduction techniques offer ways to minimize bruise when potatoes are handled in bulk throughout the facilities. One example is to run conveyor belts full of potatoes at the correct speeds to emphasize more contact with potatoes than with other hard surfaces (Thornton and Bohl 1995). IRDs have been deployed through packing facilities to determine the risk of additional bruising (Klug et al. 1989). However, once potatoes are packaged, there is less bulk handling involved and IRDs are not commonly used for assessment at this stage. Bulk or bagged potatoes are collectively put together to form a larger packaged unit of a box or bale. Once packaged into paper bales or cardboard boxes, potatoes must be palletized prior to transportation. Operations can use manual labor at this stage or have automated or robotic machinery stack boxes or paper bales on to plastic slips or wooden pallets. A plastic slip sheet is a thin piece of plastic placed underneath packaged boxes. It allows forklifts to stably move stacked boxes throughout a packing facility to prepare for shipments. The boxes often hold 22.7 kg of loose potatoes whereas baled packaging includes 2.3–4.5 kg of individually bagged potatoes. Previous research examined simulated transportation equipment for packaged potatoes and concluded shatter bruise can be caused by rough handling of packaged potatoes (Turczyn et al. 1986). Pason et al. (1990) used an IRD in shipments of apples to examine

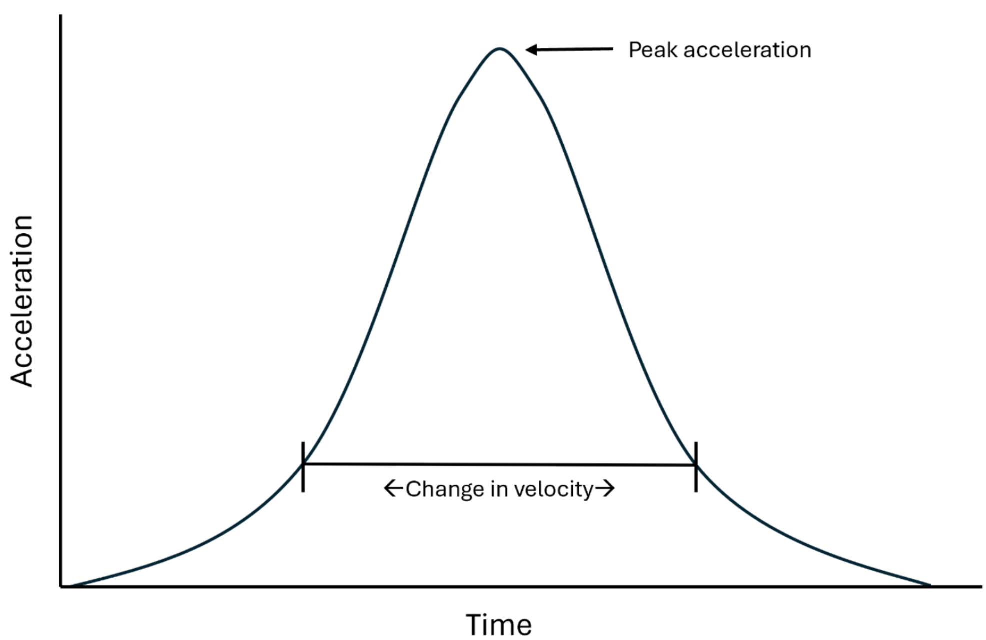

Fig. 1 Representation of the relationship between peak acceleration and velocity change during an impact. Adapted from Molema et al. (2000)

potential damage that occurred during transit although packages were not intentionally dropped. Most IRDs are placed on operating equipment, whereas Pason et al. (1990) provided context and validity for using an IRD in packaged containers rather than on equipment. This study used an IRD to examine if this last stage in packaging and palletizing at a potato packing facility was contributing to bruise and quality issues prior to transit. The objective of this study was to evaluate the potential effect drop height and impact surface have on bruise potential of packaged potatoes.

Methods and Materials

Summary of Trials

Three trials were conducted at the University of Idaho Kimberly Research and Extension Center (Kimberly, Idaho) to simulate the final stage of handling packaged russet potatoes as commonly practiced at a packing facility. An IRD (400 Series IRD©, Techmark, Inc., Lansing MI) was placed inside packaged potatoes to determine bruise potential. The IRD detects impacts with a tri-axial accelerometer and can determine impact amplitude +/- 500 g with 3% error. The IRD records the peak acceleration as maximum g force (1 g = 9.8 m/s^2) and the change in velocity. The change in velocity accounts for the impact surface and the magnitude of the impact.

The packaging materials used were a 22.7 kg cardboard box (48 × 30 × 23 cm) or a 22.7 kg paper bale. The bale was a thick brown paper bag and held five, 4.5 kg store-ready plastic bags. The cardboard box held loose Russet Norkotah potatoes. The potatoes and packaging were sourced from an Idaho packing facility.

The first trial (Trial one) examined the peak acceleration measured by the IRD in a cardboard box of potatoes when dropped from four different heights on to three surfaces with varying impact absorption capacity. The IRD was either placed in the bottom, the middle, or the top layer of the box (three locations). The middle layer was defined as having at least one layer of potatoes underneath the IRD within each box. The box was then dropped from 15, 30, 61, and 91 cm. Distance was measured from the bottom of the box to the top of the surface before being dropped. The box was dropped onto a concrete floor, a wooden pallet, or a plastic slip sheet. The plastic slip and wooden pallet were placed on top of the concrete floor. This trial was set up as a three by three by four factorial experiment and each treatment was replicated six times. The trial was conducted twice.

Trial two examined the peak acceleration measured by the IRD in cardboard boxes of potatoes when one box was dropped on to another box at different heights. The IRD was placed either in the bottom, the middle, or the top layer of the box (Fig. 2). Treatment specifies the location of the IRD within the specified box. The IRD recorded impacts from the box being dropped (Box A) as well as the stationary box (Box B). Box B was placed on a wooden pallet. Box A was dropped from 15, 30, 61, and 91 cm. Distance was measured from the bottom of Box A to the top of Box B before being dropped. Trial two was set up as a six by four factorial experiment and each treatment was replicated six times and conducted twice.

Trial three examined the peak acceleration measured by the IRD in paper bales of potatoes when dropped from different heights on to a wooden pallet or other bales (Fig. 3).

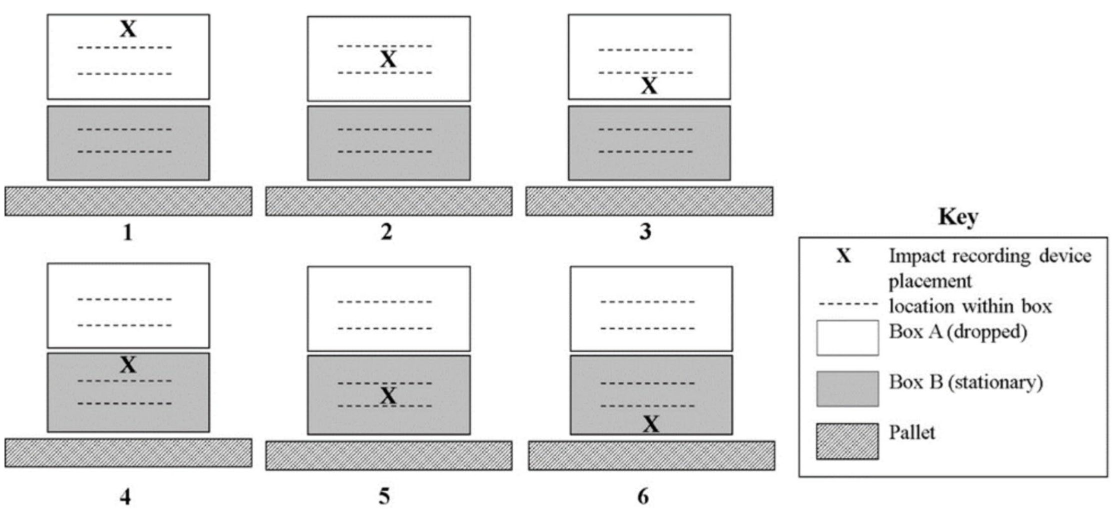

Fig. 2 Trial two treatments. All treatments were dropped onto a stationary layer of boxed potatoes on a wooden pallet, at 15, 30, 61 and 91 cm. (1) Impact recording device (IRD) placed in the top of the dropped box, (2) IRD placed in the middle of the dropped box; (3) IRD placed in the bottom of dropped box, (4) IRD placed in the top of the stationary box, (5) IRD placed in the middle of the stationary box, (6) IRD placed in the bottom of the stationary box

The IRD was placed in the middle of the bale between two 4.5 kg bags of potatoes. Treatment specifies the location of the IRD within a specified bale. There were three bales included in this trial. One bale was dropped on to a wooden pallet from 15, 30, 46, 61, and 91 cm. The next treatment had a stationary bale on the wooden pallet and an additional bale was dropped onto the stationary bale at the previously mentioned heights. The final treatment had two stationary bales on the wooden pallet and a third bale was dropped on top of these bales from the previously mentioned heights. Trial three was set up as a six by five factorial experiment and each treatment was replicated six times and conducted twice.

Statistical Analysis

The peak acceleration was analyzed using the ANOVA procedures in R (RStudio, package car version 3.0–9, 2020; Fox and Weisberg 2019). A linear model was fit for trial one where impact surface, drop height, IRD placement and the interactions were considered fixed effects. For trials two and three, placement of IRD, drop height and the interactions were considered fixed effects for the linear models. All trials' significant differences between means for response variables were compared at alpha of 0.05 by estimated marginal means procedures (Rstudio, package emmeans version 1.6.1, 2020; Lenth 2021). Impact damage risk was summarized in terms of average peak acceleration. Trial one also summarized the average velocity change to help determine bruise potential.

Results

Trial One: Boxed Potatoes Dropped from Different Heights Onto Three Surfaces

Peak accelerations ranged from 37 to 446 g and was significantly ($P < 0.0001$) influenced by the drop height of the box, the impact surface, and the IRD placement within the box (Table 1). As the drop height increased, peak acceleration increased incrementally. Dropping a box on to a wooden pallet showed a significantly lower peak acceleration than if dropped onto a plastic slip or concrete floor (Table 1). Dropping the box on to the concrete floor had the highest peak acceleration. IRD location in the box influenced the peak acceleration recorded.

An IRD positioned on the bottom of the box experienced a higher peak acceleration compared to the middle and top of the box (Table 1). The interaction between IRD location in the box and the impact surface was significant ($P < 0.0001$). The greatest difference in peak acceleration among the three materials occurred when the IRD was placed at the bottom of the box. When the IRD was located at the bottom of the box and dropped on to the pallet, the peak acceleration was 124 g which was approximately 236 g's less than dropping the box onto the plastic slip (359 g) or concrete floor (361 g; Fig. 4). There was no significant difference between the concrete surface and the plastic slip in potential impact forces experienced at the bottom of the box. The top and middle of the box had less variability in peak acceleration between surfaces, although there was significantly higher peak acceleration in the middle of the box (147 g) when dropped on to a concrete floor compared to the wooden pallet (93 g) or plastic slip (109 g). When the IRD was placed

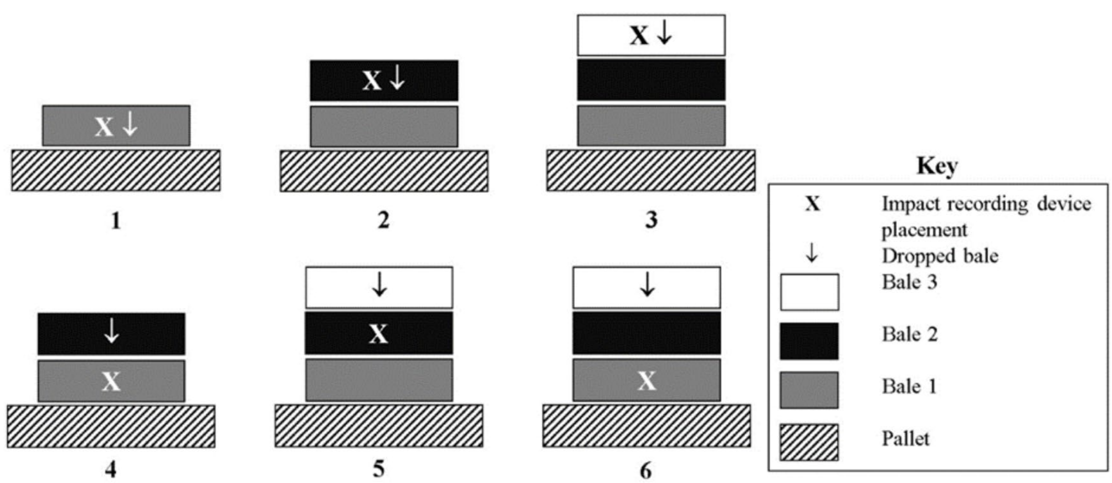

Fig. 3 Trial three treatments: (1) one bale dropped onto wooden pallet, impact recording device (IRD) placed in bale; (2) one bale dropped onto stationary bale, IRD placed in dropped bale; (3) one bale dropped onto two stationary bales, IRD placed in dropped bale; (4) one bale dropped onto stationary bale; IRD placed in stationary bale, (5) one bale dropped onto two stationary bales, IRD placed in top stationary bale, (6) one bale dropped onto two stationary bales, IRD placed in bottom stationary bale. Each treatment was carried out at 15, 30, 46, 61 and 91 cm heights

Table 1 Mean peak accelerations (max g-force) as measured by an impact recording device (IRD) located in a cardboard box filled with potatoes dropped from multiple heights onto three different impact surfaces

Drop height (cm)	Peak acceleration (max g-force)[1]
15	90 a
30	153 b
61	209 c
91	247 d
P-value	< 0.0001
Impact surface	
Wooden Pallet	132 a
Plastic Slip	188 b
Concrete	204 c
P-value	< 0.0001
Placement of IRD in box	
Top	93 a
Middle	116 b
Bottom	315 c
P-value	< 0.0001

[1]Values followed by the same letter are not significantly different (α < 0.05) for drop height, impact surface, and placement of IRD in box

in the top of the box, peak acceleration was significantly lower than the middle or bottom of the box for all impact surfaces (80 to 103 g). Boxed potatoes dropped on the concrete surface experienced a larger increase in peak acceleration with increasing drop height compared to being dropped on either the slip or wooden pallet (Fig. 5). Likewise, the largest increase in peak acceleration with increasing drop height occurred when the IRD was placed in the bottom of the box, with much less response in the middle and top locations (Fig. 6). The three-way interaction for peak acceleration between drop height, impact surface, and placement within the box was significant ($P < 0.001$; Fig. 7). The peak acceleration when the IRD was placed in the top of the box was similar when dropped at each drop height onto the pallet, slip and concrete. When the IRD was placed in the middle of the box, the peak acceleration was similar at the lower drop heights among the different impact surfaces. Although peak acceleration was much higher on concrete compared to the slip and pallet when the IRD was placed in the middle of the box and dropped from the two highest drop heights (61 and 91 cm). Peak acceleration when the IRD was placed in the bottom of the box was similar between the concrete and

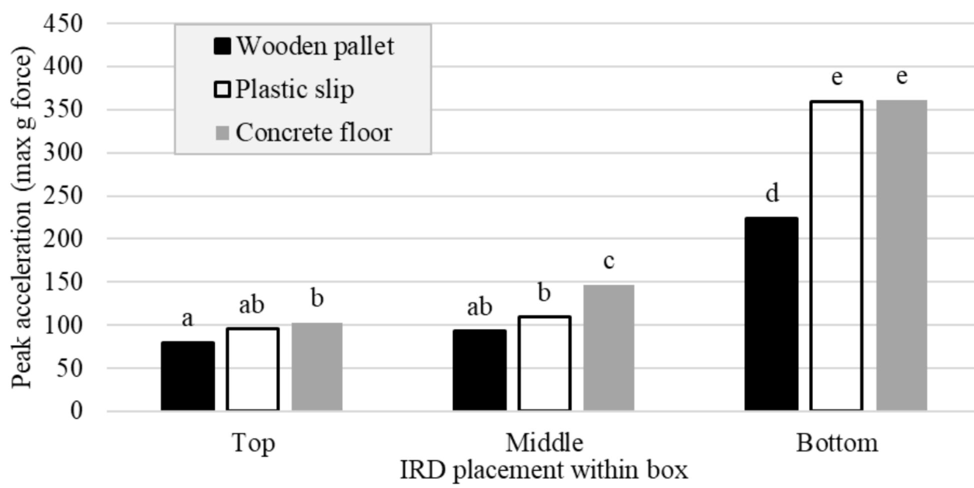

Fig. 4 Peak acceleration of the impact recording device (IRD) influenced by placement within the box (top, middle, bottom) and impact surface (wooden pallet, plastic slip, concrete floor). Bars values are the mean of peak acceleration measures for boxes dropped from 15, 30, 61, and 91 cm. Values followed by the same letter are not significantly different (α < 0.05)

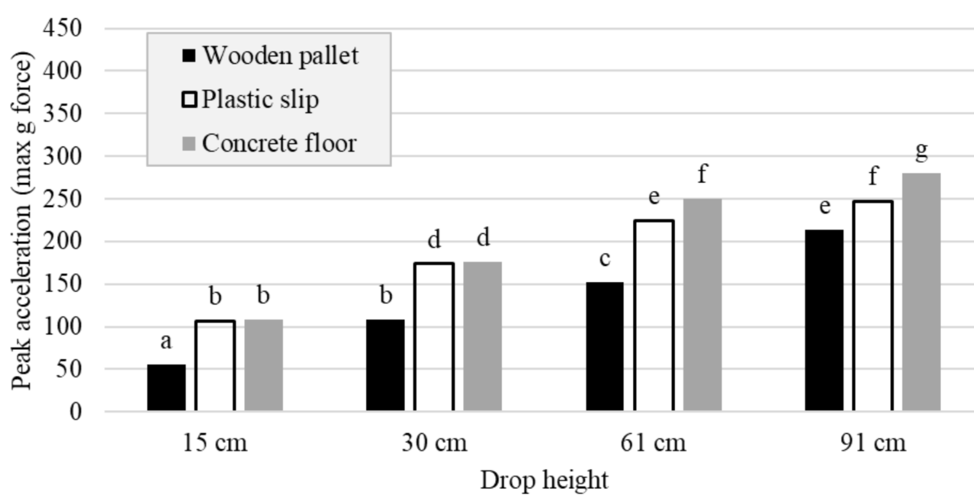

Fig. 5 Peak acceleration of the impact recording device (IRD) influenced by drop height (15, 30, 61, 91 cm) and impact surface (wooden pallet, plastic slip, concrete floor). Bars values are the mean of peak acceleration measures for boxes dropped from the top, middle, and bottom of the box. Values followed by the same letter are not significantly different (α < 0.05)

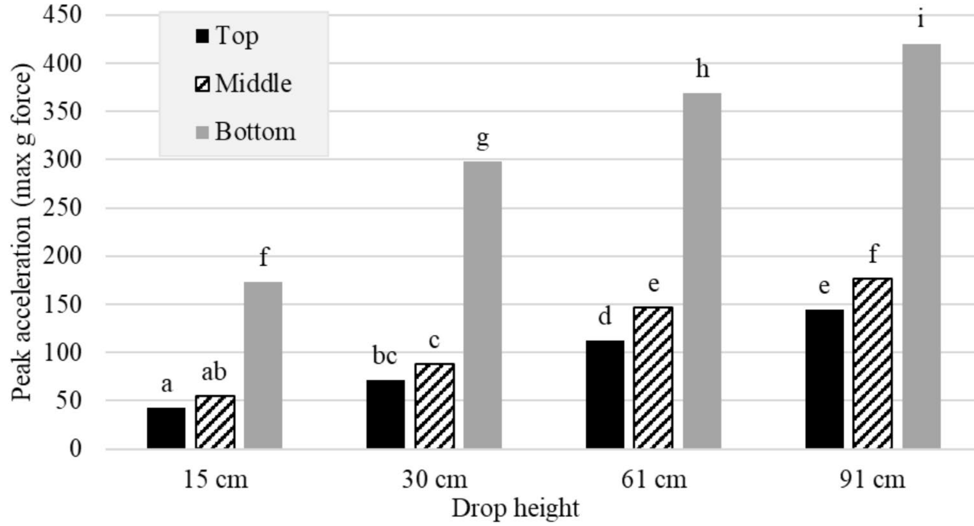

Fig. 6 Peak acceleration of the impact recording device (IRD) influenced by drop height (15, 30, 61, 91 cm) and placement within the box (top, middle, bottom). Bars values are the mean of peak acceleration measures for boxes dropped from a wooden pallet, concrete floor, and plastic slip. Values followed by the same letter are not significantly different ($\alpha < 0.05$)

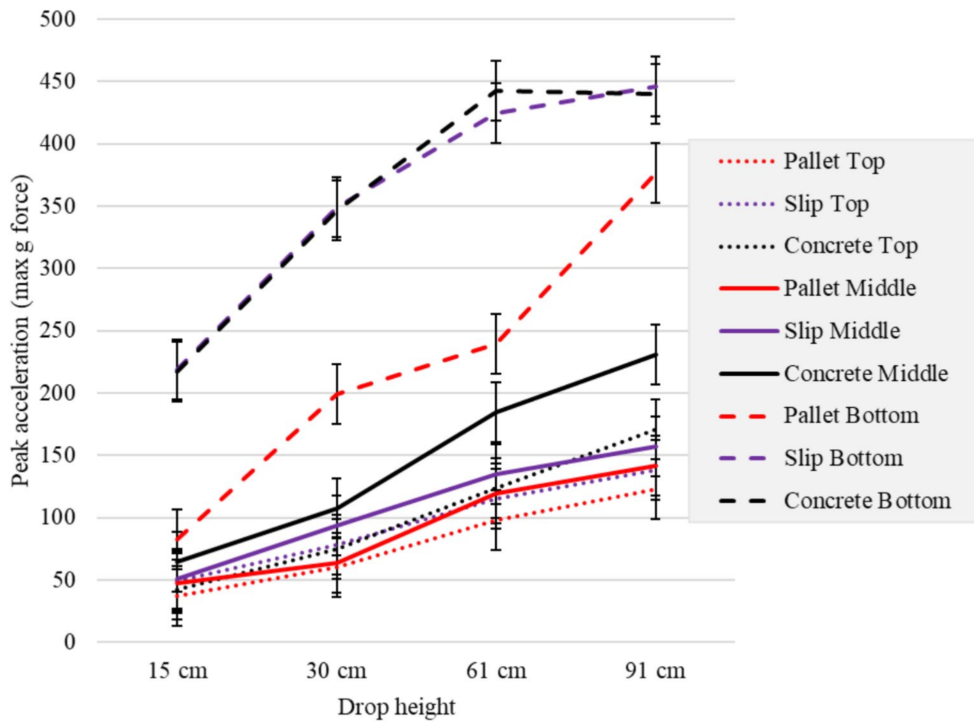

Fig. 7 Peak acceleration measured by an impact recording device (IRD; mean values ± SE) influenced by drop height (15, 30, 61, 91 cm), impact surface (wooden pallet, plastic slip, concrete floor), and placement within the box (top, middle, bottom)

slip as the drop height increased, whereas the bottom of the pallet had much lower peak accelerations at all drop heights.

The IRD used in this trial also recorded the velocity change (m/s). The relationship between peak acceleration and velocity change is described in Fig. 8. Fig. 8 uses Hyde et al. (1992) damage threshold points (100 to 375 g) to examine the bruise damage potatoes could potentially experience when boxes were dropped at different heights, on to different surfaces, and various locations within the box. The highest potential for bruise occurred in the bottom of the box, dropped from 91 cm on to concrete or a plastic slip, whereas the lowest bruise potential for the potatoes was in the top of the box when boxes were dropped from 15 cm on to a wooden pallet. These are the extreme scenarios. Drop heights above 15 cm account for most of the potential damage for the drop height variable. Although potatoes in the bottom of the box are most likely to experience damage, the top and middle of the box still have a risk of damage if dropped from high heights. Any impact surface has the potential to cause bruise damage at higher drop heights.

Trial Two: Boxed Potatoes Dropped Onto Boxed Potatoes

Overall, no peak acceleration force exceeded 100 g for this trial. Significant differences ($P = 0.04$) in peak accelerations

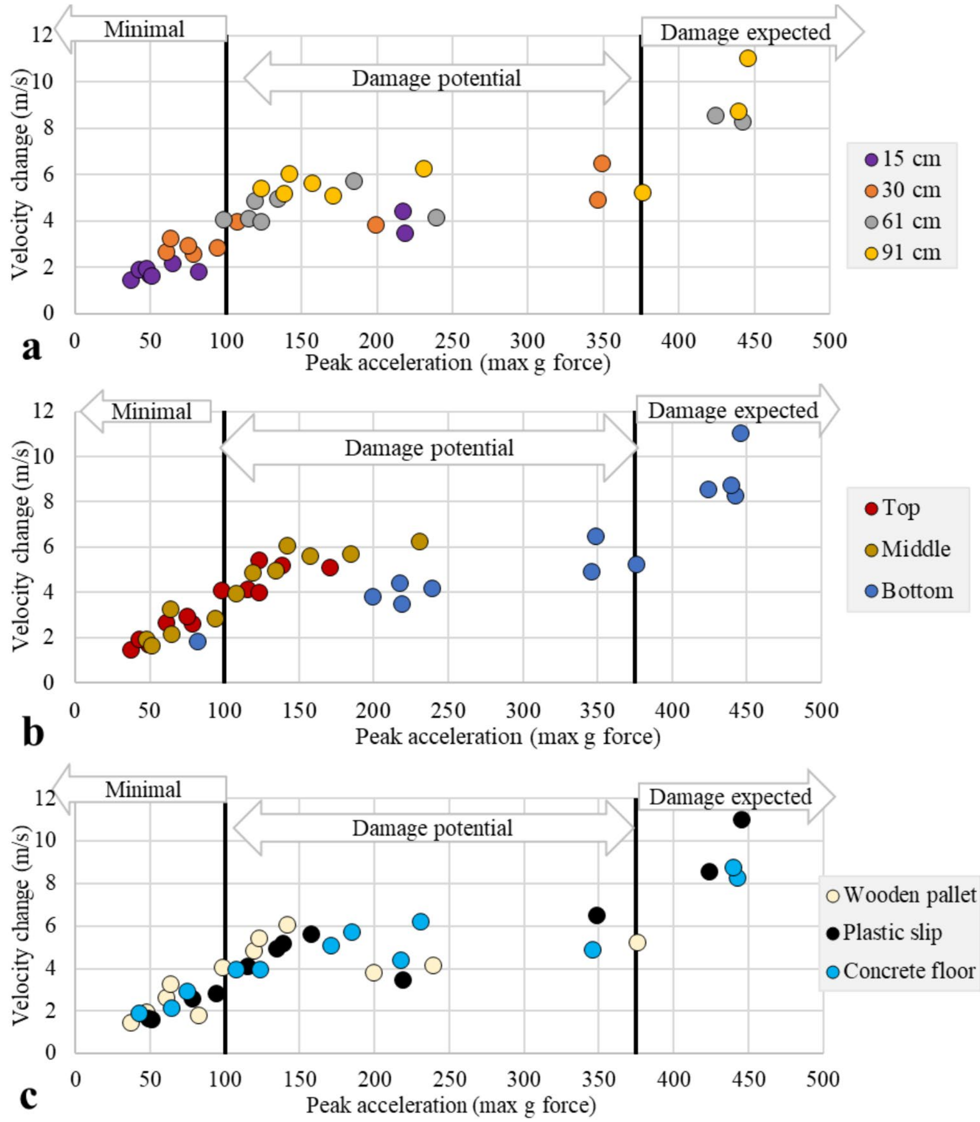

Fig. 8 Peak acceleration and velocity change relationship measured by the impact recording device (IRD) and influenced by (**a**) drop height, (**b**) impact surface, and (**c**) IRD location within the box. Data points from each graph are the same but colored differently to reflect the treatments. Hyde et al. (1992) determined bruise potential was low when peak acceleration was below 50 g, high when above 100 g, and certain damage over 375 g. The major bruise potential zone was determined to be between 100 and 375 g (depicted by black vertical lines) and a high likelihood of physical damage

Table 2 Mean peak accelerations (max g-force) as measured by an impact recording device (IRD) located in a cardboard box filled with potatoes dropped from multiple heights on to stationary boxed potatoes

Treatment	Peak acceleration (max g-force)[1]
Dropped box; IRD-top	43 bc
Dropped box; IRD-middle	39 ab
Dropped box; IRD-bottom	42 bc
Stationary box; IRD-top	49 c
Stationary box; IRD middle	39 ab
Stationary box; IRD bottom	32 a
P-value	0.04
Drop height (cm)	
15	20 a
30	35 b
61	45 c
91	63 d
P-value	< 0.0001

[1]Values followed by the same letter are not significantly different (α < 0.05) for treatment and drop height

due to treatment and drop height were observed. There were significant differences in peak acceleration when the IRD was placed in the bottom of the stationary box (32 g) compared to the top of the stationary box (49 g). Peak acceleration was similar in the dropped box (39 to 43 g) regardless of the placement of the IRD (Table 2). Peak acceleration incrementally increased as drop height increased (Table 2). There was a significant interaction in peak acceleration between treatment and drop height ($P = 0.0005$). The treatments had more variability in peak acceleration at the 91 cm drop height (44 to 85 g) compared to the 61 cm drop height (38 to 59 g) or the 30 cm drop height (24 to 50 g). No significant differences among the six treatments were observed at the 15 cm drop height (Fig. 9).

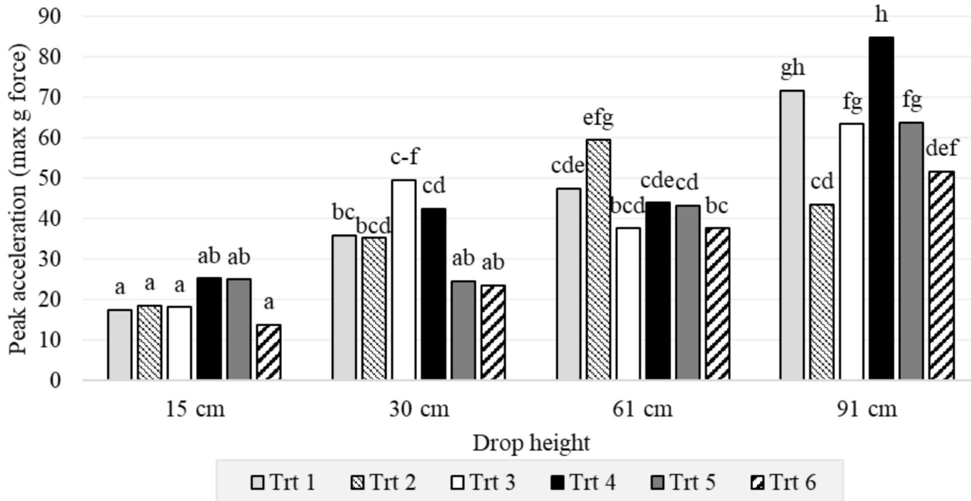

Fig. 9 Peak acceleration measured by an impact recording device (IRD) influenced by drop height (15, 30, 61, 91 cm), and treatment (IRD placement: top, middle or bottom of box) when boxes were dropped on other boxes (stationary or dropped box). Trt = Treatment. Trt (1) Impact recording device (IRD) placed in the top of the dropped box, Trt (2) IRD placed in the middle of the dropped box; Trt (3) IRD placed in the bottom of dropped box, Trt (4) IRD placed in the top of the stationary box, Trt (5) IRD placed in the middle of the stationary box, Trt (6) IRD placed in the bottom of the stationary box. Values followed by the same letter are not significantly different ($\alpha < 0.05$) for each graph

Table 3 Mean peak accelerations (max g-force) as measured by an impact recording device (IRD) located in a paper bale and dropped from multiple heights onto packaged potatoes on a wooden pallet

Treatment		
Location where bale was dropped	IRD location	Peak acceleration (max g-force)[1]
Wooden pallet	Dropped bale	47
One stationary bale	Dropped bale	46
Two stationary bales	Dropped bale	38
One stationary bale	Stationary bale	43
Two stationary bales	Top stationary bale	57
Two stationary bales	Bottom stationary bale	20
P-value		0.09
Drop height (cm)		
15		21 a
30		32 ab
48		45 bc
61		53 c
91		58 c
P-value		0.002

[1]Values followed by the same letter are not significantly different ($\alpha < 0.05$) for treatment and drop height

Trial Three: Baled Potatoes Dropped at Various Heights

This trial examined peak accelerations when a bale of potatoes was dropped either on to a wooden pallet or other bales of potatoes (Fig. 3). Overall, peak acceleration force did not exceed 60 g for this trial and differences in means between treatments were not as large as seen in the other trials ($P = 0.09$; Table 3). Peak acceleration significantly increased as drop height increased (21 to 58 g; Table 3). There was no significant interaction between treatment and drop height ($P = 0.87$).

Discussion

Although IRDs are intended to mimic the potential for a damaging impact force to an individual tuber as it moves through handling equipment, this study used the IRD to gather information about how a potato within a box or bale of potatoes would respond to being dropped. Peak acceleration and velocity change have been used in previous studies to develop bruise risk management strategies. Praeger et al. (2013) found peak acceleration is a practical tool to determine whether potatoes in handling operations are surpassing a bruise threshold. Hyde et al. (1992) determined that bruise potential is low when peak acceleration is below 50 g, high when peak acceleration is above 100 g, and visible bruise damage occurs over 375 g. When recorded peak acceleration is within the major bruise potential zone (between 100 and 375 g), the next step is to determine how to minimize the large impacts.

One caveat about IRD technology is that it only measures impact force, not tuber characteristics, which may also influence bruise susceptibility and how the tuber responds to the impact force. Previous research has identified methods to determine bruise thresholds using an IRD (Bajema and Hyde 1998; Hyde et al. 1992; Mathew and Hyde 1997; Rady and Soliman 2015). A bruise threshold is defined as the impact force required to damage a potato, but tuber pulp temperature, (Thornton et al. 1973; Smittle et al. 1974; McGarry et al. 1996; Baritelle and Hyde 2001; Xie et al. 2020), cultivar (Blahovec and Židová 2004; Kunkel et al. 1978; Horvath 1986), and tuber hydration (Kunkel and Gardner 1965; Thornton and Timm 1990) are examples of factors that can alter bruise susceptibility and influence the bruise threshold. Rather than create a bruise threshold, this study provided contextual data to aid in determining package handling scenarios that could increase the risk for bruise.

The results from the trials in this study showed that boxes dropped on to a concrete floor, or a plastic slip over a concrete floor, have the highest risk of damage, especially for potatoes in the bottom of the box. The potatoes at the bottom of the box will encounter a peak acceleration of 200 max g-force even at a low drop height of 15 cm. The risk of damage is lower for potatoes in the top or middle of the box. When drop heights were lowered, or when cushioning material was added to a hard surface (a wooden pallet), risk of damage decreased throughout the box. However, all drop heights and impact surfaces evaluated in this study had the potential to influence damage to potatoes located throughout the box. The combination of all three variables will dictate the severity of damage. For instance, the top and middle of the box were less likely to experience damage when dropped from heights below 30 cm on any impact surface. When the drop height was increased to 61 to 91 cm, potatoes were more likely to experience damage, regardless of the surface. Potatoes in the bottom of the box were less likely to experience damage when potatoes were dropped from 15 cm and on to a wooden pallet. Regardless of the impact surface, the potatoes on the bottom of the box have an increased risk of damage. When palletizing boxed potatoes, the risk of bruise decreased after the first layer was stacked on the pallet. This result reinforced the importance of modifying the potential impact packaged potatoes experienced on the initial layer of the pallet. The main issue was not subsequent packing of boxes on top of each other but rather the initial box being dropped on the concrete floor, plastic slip, or wooden pallet. For the initial layer during palletization of boxed potatoes, the results imply that the best handling practices would be those that avoid dropping boxes more than 15 cm regardless of impact surface. Peak accelerations did not exceed 100 g's when packaged potatoes were dropped on to other boxes and/or bales, reinforcing the concept that potatoes can withstand greater impact when dropped onto other potatoes as concluded by Rady and Soliman (2015). Handling procedures for humans and calibration for robotics need to emphasize drop height clearances.

The risk of high peak accelerations was not seen in the dropped or stationary bales for any of the drop heights examined. In a paper bale, potatoes are packaged tightly within the bale unlike boxes where potatoes are loose and have greater potential for movement within the box. The tighter packaging in paper bales could explain the overall low peak accelerations observed. In contrast, Turczyn et al. (1986) found cardboard boxes provided greater protection against shatter bruise than a paper bale, although the Turczyn et al. study used bagged potatoes within the cardboard box treatment whereas the current study used loose potatoes in the boxes. This contradictory finding suggests loose potatoes in packaging can have a large impact on the potential for damage. Future research could further examine the relationship between the IRD findings and quantified damage of the potatoes in paper bales.

A wooden pallet was used as a cushioning material for this study and was found to soften the impact compared to a concrete floor or a plastic slip. Wooden pallets are used worldwide to transport goods but can be an additional cost to the packer due to purchasing, sorting, and inspecting for damage (Mumford 2002). The plastic slip used in this study provided slightly better protection from damage over the concrete floor, except for potatoes at the bottom of the box. There was no difference between the plastic slip and concrete floor at lower drop heights, but this protection could be seen at the 61 and 91 cm drop heights. Modifying the plastic slip to include greater cushioning potential could provide an alternative for wooden pallets.

Conclusion

As fresh market potatoes are packaged into boxes or bales and placed on pallets in preparation for shipping, there is potential for bruise to occur. The results from the trials implemented in this study using an IRD to measure impact potential show that this bruise potential is minimized as boxes and bales are dropped from lower heights and cushioned with the use of wooden pallets. However, the potatoes at greater risk for bruise are in the bottom of the boxes. Increased cushioning for the bottom layer of potatoes during palletization in packing facilities could lower the risk of bruise. This study provided information for educating personnel on handling packaged potatoes and adjusting robotic palletizing machines regarding heights at which they drop potatoes. In addition, it determined that drop heights need to be below 15 cm, especially when making the first layer in a palletized stack of packaged potatoes, to reduce the risk of bruise damage. Cushioned plastic slips could provide an alternative to wooden pallets. Future research should assess bruise damage that occurs to actual potatoes when boxes and bales are dropped to further explain the risk associated with improper handling of packaged potatoes.

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Authors Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Rabecka Hendricks and Nora Olsen. The first draft of the manuscript was written by Rabecka Hendricks and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

References

Bajema, R. W., and G. M. Hyde. 1998. Instrumented pendulum for impact characterization of whole fruit and vegetable specimens. *American Society of Agricultural Engineers* 41(5): 1399–1405. https://doi.org/10.13031/2013.17274.

Baritelle, A. L., and G. M. Hyde. 2001. Commodity conditioning to reduce impact bruising. *Postharvest Biology and Technology* 21: 331–339.

Bentini, M., C. Caprara, and R. Martelli. 2006. Harvesting damage to potato tubers by analysis of impacts recorded with an instrumented sphere. *Biosystems Engineering* 94(1): 75–85. https://doi.org/10.1016/j.biosystemseng.2006.02.007.

Blahovec, J., and J. Židová. 2004. Potato bruise spot sensitivity dependence on regimes of cultivation. *Research in Agricultural Engineering* 50(3): 89–95.

Deng, W., C. Wang, and S. Xie. 2020. Impact peak force measurement of potato. *International Journal of Food Properties* 23(1): 616–626.

Fox, J., S. Weisberg. An {R} companion to applied regression, third edition. Thousand Oaks CA:, and Sage. 2019. https://socialsciences.mcmaster.ca/jfox/Books/Companion/.

Hollingshead, A., R. Hendricks, N. Olsen, and M. Thornton. 2020. Monitoring tools for a potato bruise prevention program. In *Bulletin 966*, Moscow, ID: University of Idaho.

Horvath, S. 1986. Possibilities for decreasing tuber damage caused by mechanization. In *Engineering for Potatoes*, ed. B. F. Cargill. 99–106. MI: American Society of Agricultural Engineers, E. Lansing.

Hyde, G. M., R. E. Thornton, and R. E. Hermanson. 1988. Reducing potato harvesting bruise. Cooperative Extension Bulletin 1080. Washington State University, Pullman, WA.

Hyde, G. M., G. K. Brown, E. J. Timm, and W. Zhang. 1992. Instrumented sphere evaluation of potato packing line impacts. *American Society of Agricultural Engineers* 35(1): 65–69.

Klug, B. A., B. R. Tennes, and H. R. Zapp. 1989. Analysis of impact recorded with an instrumented sphere. *American Society of Agricultural Engineers* 32(3): 1105–1110.

Kunkel, R., and W. H. Gardner. 1965. Potato tuber hydration and its effect on blackspot of Russet Burbank potatoes in the Columbia Basin of Washington. *American Potato Journal* 42: 109–124.

Kunkel, R., W. H. Gardner, N. M. Holstad, and T. S. Russell. 1978. Blackspot and potato fertilization in Washington's Columbia Basin. Bulletin 862. Washington State University, Pullman, WA.

Lenth, R. L. 2021. Emmeans: Estimated marginal means, aka least-squares means. R package version 1.6.1. https://CRAN.R-project.org/package=emmeans.

Manetto, G., E. Cerruto, S. Pascuzzi, and F. Santoro. 2017. Improvements in citrus packing lines to reduce the mechanical damage to fruit. *Chemical Engineering Transactions* 58: 391–396.

Mathew, R., and G. M. Hyde. 1997. Potato impact damage thresholds. *Transactions of the ASAE* 40: 705–709. https://doi.org/10.13031/2013.21290.

McGarry, A., C. C. Hole, R. L. K. Drew, and N. Parsons. 1996. Internal damage in potato tubers: a critical review. *Postharvest Biology and Technology* 8(4): 239–258. https://doi.org/10.1016/0925-5214(96)00006-3.

Molema, G. J., P. C. Struik, B. R. Verwijs, A. Bouman, and J. J. Klooster. 2000. Subcutaneous tissue discoloration in ware potatoes. 2. Impact measured by an instrumented sphere. *Potato Research* 43: 225–238.

Mumford, J. D. 2002. Economic issues related to quarantine in international trade. *European Review of Agricultural Economics* 29(3): 329–348.

Pason, N. L. S., E. J. Timm, G. K. Brown, D. E. Marshall, and C. L. Burton. 1990. Apple damage assessment during intrastate transportation. *Applied Engineering in Agriculture* 6(6): 753–758.

Pothula, A. K., Z. Zhang, and R. Lu. 2018. Design features and bruise evaluation of an apple harvest and in-field presorting machine. *Transactions of the American Society of Agricultural and Biological Engineers* 61(3): 1135–1144.

Praeger, U., J. Surdilovic, I. Truppel, B. Herold, and M. Geyer. 2013. Comparison of electronic fruits for impact detection on a laboratory scale. *Sensors (Basel, Switzerland)* 13: 7140–7155.

Rady, A. M., and S. N. Soliman. 2015. Evaluation of mechanical damage of Lady Rosetta potato tubers using different methods. *International Journal of Postharvest Technology and Innovation* 5(2): 125–148.

Sargent, S. A., J. K. Brecht, and J. J. Zoellner. 1992. Instrumented sphere impact analyses of tomato and bell pepper packing lines. *Applied Engineering in Agriculture* 8(1): 76–83.

Smittle, D. A., R. E. Thornton, C. L. Peterson, and B. B. Dean. 1974. Harvesting potatoes with minimum damage. *American Potato Journal* 51: 152–164.

Thomson, G. E., and J. P. Lopresti. 2018. Size and temperature characteristics of potatoes help predict injury following impact collisions. *New Zealand Journal of Crop and Horticulture Science* 46(1): 1–17.

Thornton, M., and W. Bohl. 1995. Preventing potato bruise damage. Extension Bulletin 725. University of Idaho, Moscow, ID.

Thornton, R. E., and H. Timm. 1990. Influence of fertilizer and irrigation management on tuber bruising. *American Potato Journal* 67: 45–54.

Thornton, R., D. A. Smittle., and C. L. Peterson. 1973. Reducing potato damage during harvest. Extension Bulletin 646. Washington State University, Pullman, WA.

Turczyn, M. T., S. W. Grant, B. H. Ashby, and F. W. Wheaton. 1986. Potato shatter bruising during laboratory handling and transport simulation. *American Society of Agricultural Engineers* 29(4): 1171–1175.

USDA. 2019. *Crop production historical Track records*. 2157–8990. United States Department of Agriculture, National Agricultural Statistics Service.

USDA. 2022. *Potatoes 2021 summary. United States Department of Agriculture, National Agricultural Statistics Service*. ISSN: 1949–1514.

Xie, S., C. Wang, and W. Deng. 2020. Experimental study on collision acceleration and damage characteristics of potato. *Journal of Food Process Engineering* 43: 1–7.