In vitro evaluation of nonrigid support systems for the equine metacarpophalangeal joint

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Summary

Metacarpophalangeal (MCP) joint extension is primarily resisted by the digital flexortendons and suspensory ligament. A variety of external support techniques are used to protect these supporting structures from or after injury by resisting MCP joint extension, although not all are effective and/or practical for use in an exercising horse. In this study, 7 forelimbs were loaded *in vitro* to determine the effect of a simple gamgee bandage, a 3-layered bandage with and without a contoured palmar splint, a neoprene exercise boot, and an innovative carbon fibre composite exercise boot (Dalmar tendon support boot). There was no significant resistance to MCP joint extension by the gamgee or neoprene exercise boot. The 3-layered bandage had a significant (P<0.01) supporting effect at MCP angles of ≥ 245°, and when combined with the contoured splint at angles of ≥ 230°. The Dalmartendon support boot resisted MCPextension at angles of ≥ 245° (settings 1 and 2) and ≥ 225° (setting 3). These data demonstrate that the contoured splint and the Dalmar tendon support boot (which is also easily fitted for use during exercise) are useful for the management of tendon/ligament injury and during rehabilitation.

Introduction

Extension of the metacarpophalangeal (MCP) joint by the ground reaction force is primarily resisted by 3 supporting tendons and ligaments on the palmar side of the limb: 1) the *musculus interosseous medius* (suspensory ligament) and its continuation, via the proximal sesamoid bones, the distal sesamoidean ligaments; 2) the superficial digital flexor tendon via its accessory ligament and muscle belly; and 3) the deep digital flexor tendon, via both its accessory ligament and muscle belly (Stashak 1987).

The muscle bellies associated with the deep and superficial digital flexor tendons are highly pennate with extremely short muscle fibres (Hermanson and Cobb 1992) and contraction of these muscles has minimal effect on MCP joint angle in the standing horse (McGuigan 2001; Wilson *et al.* 2002). Resistance to extension of the MCP joint is, therefore, primarily a passive process, with these tendons and ligaments acting as linearly elastic springs. Therefore, an increase in MCP joint angle results in increased strain in the tendon and ligaments (Herbst 1895; Camp and Smith 1942; Bartel *et al.* 1978; Rooney *et al.* 1978; Riemersma *et al.* 1988; Shoemaker *et al.* 1991). The superficial digital flexor tendon and suspensory ligament have been shown to reach strains of greater than 10% during high speed locomotion (Lochner *et al.* 1980; Stephens *et al.* 1989; Riemersma *et al.* 1996). The magnitude of these strains is similar to that which would cause mechanical failure of tendon *in vitro*. Therefore, hyperextension of the MCP joint beyond its normal range of motion involves the risk of injury to these structures (Riemersma and Schamhardt 1985).

Since MCP joint extension is essentially a passive event due to limb vertical force, hyperextension of the joint occurs either when vertical limb force is increased (Merkens and Schamhardt 1994) or if one of the 3 supporting structures is compromised and MCP joint extension is resisted only by the remaining tissues (McIlwraith 1987). Increased vertical limb force results from a variety of external factors including high-speed exercise, hard ground surface, increased weight of rider and incoordination (Schryver *et al.* 1978; McIlwraith 1987; Schamhardt *et al.* 1991; McLaughlin *et al.* 1996).

Tendon injury is believed to occur as a result of cyclical loading causing cumulative fatigue damage (Wang *et al.* 1995; Smith *et al.* 1999) with one or more episodes of tendon overstrain superimposed (Webbon 1973; Smith *et al.* 1999; Dowling *et al.* 2000). The former is possibly determined by the magnitude and intensity of training load (as for bone; Nunamaker *et al.* 1990) in combination with various environmental factors such as surface and hoof angle (Lochner *et al.* 1980; Stephens *et al.* 1989; Riemersma *et al.* 1996). The latter has been attributed to increased impact loads due to fatigue, stumbling or jump landing (Webbon 1973; Dowling *et al.* 2000). The weightbearing digital flexor tendons of the equine limb appear not to respond to mechanical stimuli in the mature horse (Birch *et al.* 1999; Smith *et al.* 1999) and, therefore, unlike bone, high strains appear unnecessary to maintain full mechanical competence. Therefore, an externally

applied mechanical support that resists overextension of the MCP joint reduces the potentially damaging peak loads and strains in the palmar supporting soft tissue structures (Bartel *et al.* 1978; Reimersma *et al.* 1988). This may be beneficial in reducing the risk of injury and re-injury to these structures (Riemersma and Schamhardt 1985).

Nonrigid support bandages are often placed on the distal limbs of horses in an attempt to provide protection and mechanical support to the flexor tendons and suspensory ligaments during athletic activity. Bandaged legs have been reported to absorb significantly more energy than unbandaged limbs when loaded *in vitro* and, hence, reduce the overall energy available for tissue disruption (Crawford *et al.* 1990). Whereas bandaging reduces fetlock extension during weightbearing in horses exercised to fatigue (Kobluk *et al.* 1988), it does not alter the maximal strain on the suspensory ligament when standing or at the walk (Keegan *et al.* 1992). It is unclear whether such bandages achieve their reported effects by direct mechanical support or if they function, as is the case in taping of ankle joints in sportsmen, by enhancing proprioception (Robbins *et al.* 1995).

The effect of damage to one element of this supporting apparatus is 2-fold: 1) the force transmitted by each of the other elements is increased and 2) the joint extends beyond its normal angle for that limb force and the strain in all 3 structures is therefore increased (Sisson 1975; McIlwraith 1987; Stashak 1987).

The degree of MCP joint hyperextension is greatest in cases of total traumatic disruption of the suspensory apparatus. Suspensory desmitis (Moyer and Raker 1980) and flexor tendon laceration (Bertone 1995) both lead to lesser degrees of hyperextension of the MCP joint. Laceration of the flexor tendons is a relatively common occurrence in palmar/plantar metacarpal/metatarsal penetrating injuries (Bertone 1995). These injuries are commonly managed with surgical debridement, repair with or without implants, and external coaptation (McIlwraith 1987). The external coaptation resists MCP joint extension and augments the role of the damaged structure while it heals.

Provision of MCP joint support is particularly important in cases where tendon ends have been sutured. A sutured tendon fails at about 1% of the force of a healthy tendon (Jann *et al.* 1990) and support is therefore vital if the tendon ends are to remain in apposition (Foland *et al.* 1991). Mechanical loading is, however, important in the healing process and, while rigid external coaptation protects the injured tendons and ligaments from mechanical overload, there is a sudden increase in tissue loading when the cast is removed. Because the rest of the tendon is relatively stiff, the repairing tissues are vulnerable to such sudden increases in forces transmitted by the tendon, causing further damage. This results in an elongated tendon, more scar tissue and re-initiation of the healing process with a protracted recovery. Ideally, the support provided to the MCP joint should be reduced gradually after cast immobilisation to increase progressively the load experienced by the healing tissues. This can be achieved by the use of a less rigid support system, which can be applied immediately after the cast is removed.

In this study, we tested independent hypotheses that 2 conventional support bandage styles, a palmar splint and 2 proprietary tendon support boots would provide significant mechanical resistance to MCP joint extension in an *in vitro* loading system.
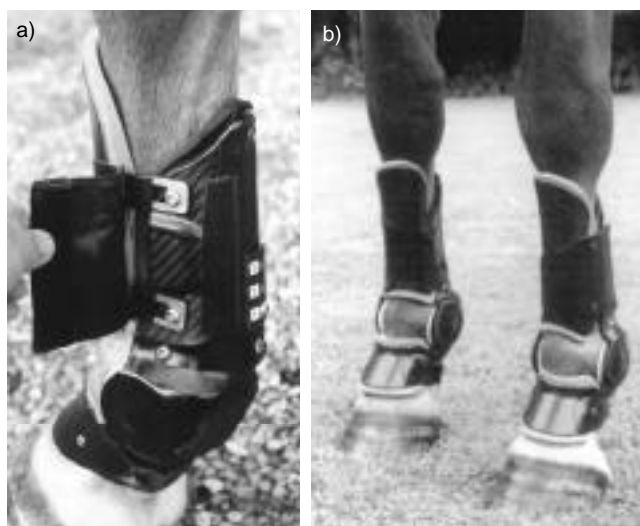

Fig 1: The Dalmar tendon support boot used in this study.

Materials and methods

Seven equine forelimbs were obtained *postmortem* from Thoroughbred-type horses with no signs of distal limb injury and stored at -20°C until required. Each limb was allowed to thaw to room temperature for 12 h prior to preparation and testing.

The carpus was disarticulated through the middle carpal joint to maintain the proximal attachment of the suspensory ligament, and a 12 mm diameter hole drilled centrally through the third carpal and third metacarpal bones to accommodate the pin of the loading ram. Limbs were located in a pneumohydraulic loading machine (Hydraulic Test Rig)[1]. Axial load was applied using a hydraulic ram and the force acting on the limb recorded through a plate and shear beam load cell (TW560)[2] mounted under the hoof. MCP joint angle was recorded via a goniometer attached to 6 mm diameter pins drilled into the proximal third metacarpal bone and the laterodorsal hoof wall and distal phalanx. Force and angle data were amplified via strain gauge amplifiers, logged via a 12 bit A/D converter to a personal computer using LabView[3] data capture software and stored for subsequent analysis using a spreadsheet programme (Microsoft Excel)[4]. Each limb was subjected to the following loading regime.

The limb was loaded to a peak force of 5 kN (equivalent to the load experienced at the trot in a 500 kg horse [10 N/kg body mass]; Wilson *et al.* 2001) over a period of 5 s and then unloaded at the same rate. This load created a similar MCP joint angle to that recorded during gallop locomotion, due to the lack of deep and superficial digital flexor muscle bellies and the accessory ligament of the SDFT. The loading cycle was then repeated to ensure that the limb had bedded into the jig. Two further loading cycles were then applied, during which limb force and MCP joint angle were recorded.

The following support methods were then applied in the same sequence for each limb, with the limb loaded twice in each state. The second loading cycle was used in the analysis to allow for any 'bedding in' of the support technique. Between each augmented loading, a control (bare leg) loading was recorded. All augmentation techniques were applied by the same person.

The Dalmar tendon support boot[5] (Fig 1)

This is an innovative adjustable tendon support system designed to provide a controlled resistance to MCP joint extension while

TABLE 1: Mean ± s.d. effects on limb force (kN) at specific MCP joint angles for the different support techniques

MCP angle (°)	Limb force (kN)						
	Gamgee	Robert Jones	Palmar splint	Neoprene	Dalmar 1	Dalmar 2	Dalmar 3
215	0.04 (0.16)	0.00 (0.12)	-0.12 (0.31)	0.04 (0.08)	0.02 (0.05)	0.05 (0.11)	0.01 (0.12)
220	0.06 (0.13)	0.05 (0.16)	0.05 (0.30)	0.02 (0.06)	0.04 (0.06)	0.10 (0.04)	0.06 (0.09)
225	0.08 (0.13)	0.11 (0.20)	0.22 (0.30)	0.01 (0.06)	0.06 (0.09)	0.06 (0.12)	0.18 (0.15)[#]
230	0.11 (0.15)	0.18 (0.25)	0.41 (0.31)[#]	0.01 (0.07)	0.08 (0.10)	0.11 (0.15)	0.38 (0.24)[#]
235	0.15 (0.19)	0.26 (0.29)	0.59 (0.33)[#]	0.02 (0.06)	0.10 (0.10)	0.19 (0.20)	0.63 (0.35)[#]
240	0.19 (0.23)	0.35 (0.32)	0.77 (0.34)[#]	0.03 (0.06)	0.11 (0.10)	0.29 (0.25)	0.96 (0.48)[#]
245	0.24 (0.27)	0.46 (0.37)[#]	0.96 (0.36)[#]	0.06 (0.07)	0.13 (0.07)[#]	0.43 (0.32)[#]	1.36 (0.64)[#]
250	0.29 (0.33)	0.58 (0.41)[#]	1.15 (0.40)[#]	0.09 (0.10)	0.14 (0.12)[#]	0.59 (0.40)[#]	1.83 (0.83)[#]

[#]Significance (P<0.01) relative to zero.

allowing full flexion of the joint. It is intended as both a treatment of injured tendons and for prevention of overstrain injury in exercising horses. The boot consists of semirigid carbon fibre composite sheaths that enclose the metacarpal and proximal phalangeal regions. These are joined by a hinge joint that pivots concentrically with the horse's MCPjoint. The boot is adjusted to fit the leg with ski boot type bindings and a foam lining conforms to any variability in the shape of a horse's leg. A Kevlar fibre tensile support element runs along the palmar aspect of the metacarpus and digit and is anchored to each end of the boot. The boot resists MCP joint extension by means of the inherent compression strength of the carbon fibre joint combined with the tensile strength of the kevlar fibres. The amount of resistance that the system provides to MCP joint extension is a function of the position of an adjustment control which has 3 settings. The different settings change the length of the Kevlar tensile support element. At setting 1, the support element is at its longest and hence slackest length, offering the least amount of support; while at setting 3, the tensile element is shortest, offering the greatest degree of support to the MCPjoint. The boot has a mass of about 200 g, similar to that of other exercise boots.

The sports medicine boot[6]

This is a commercially available neoprene elasticated equine support boot that wraps around the palmar aspect of the metacarpus and under the MCP joint, is tensioned by hand and held in place by Velcro straps.

A simple gamgee bandage

A single layer of gamgee tissue[7] was held in place by a roll of flexible cohesive bandaging tape (Co-Plus)[8].

A modified Robert Jones distal limb bandage

This was a 3-layered bandage consisting of a full roll of cotton wool (Propax)[8] compressed with 3 rolls of 15 cm open weave stretch bandage (K-band)[9] followed by a roll of flexible cohesive bandaging tape (Co-Plus)[8].

A contoured palmar splint

This splint was applied to the palmar aspect of the modified Robert Jones bandage. It was constructed from a single roll of 12.5 cm casting tape (VetCast Plus)[10] which was moulded in longitudinal layers to fit the combined length of the metacarpus and pastern, from the proximal metacarpus to the bulbs of the heel. It was fixed in position on the bandaged limb in a neutral position (210° of extension in this study) by wrapping a second roll of 5 inch wide casting tape circumferentially around the limb. Once the casting tape had cured, the splint was cut from the remainder of the transversely positioned casting tape by a longitudinal cut either side of the splint with a plaster saw. The splint was then applied to the bandaged limb and taped in position using plastic agricultural tape. Previous experience in clinical cases had demonstrated tearing of the tape in the phalangeal region, and multiple layers of tape were therefore used in this region. The same splint was used for all limbs.

Data analysis

A limb force-MCP joint angle curve was plotted for each loading cycle in a spreadsheet programme[4]. A second order polynomial regression curve was calculated for each curve and used to calculate the force for each degree increment of MCP joint angle. These values were used in the subsequent analysis to enable intra- and interlimb averaging and calculation of mean effects. A support effect for each system on each limb was calculated by subtracting the force-angle curve for that system from the associated control loading curve (the mean of the unsupported limb loading curve generated immediately before and after the individual trial). These effects were then used to calculate mean effect curves for each system across all the legs.

Statistical analysis of the effects of the various support techniques was undertaken by comparing the limb force at a range of MCP joint angles in the unsupported limb to that observed at the same joint angles with each support system. Paired *t* tests were used and a significance level of P<0.01 was chosen because of the large numbers of comparisons involved.

Results

The mean unsupported limb second order polynomial curve is shown in Figure 2. This represents the relationship between limb force and MCPjoint angle for the group of limbs. In Figures 3 and 4, the effect of each support system are seen. These represent the additional force applied to the leg to achieve the same MCPjoint angle and, added to the data in Figure 2, produce a mean curve for an augmented limb. All polynomial curves had r^2 >0.99. Table 1 shows the mean ± s.d. limb force effect for the group of legs at a range of MCPjoint angles experienced during normal locomotion. The simple gamgee bandage and the neoprene boot had no
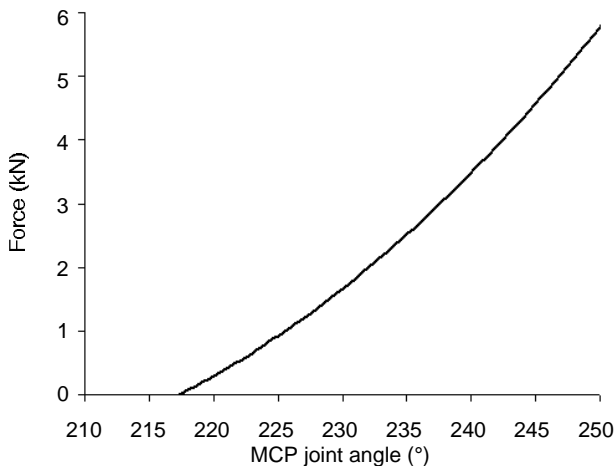
Fig 2: Mean relationship between limb force and MCP joint angle for an isolated distal limb (n = 6).

Fig 3: Mean ± s.e. support effect for the neoprene exercise boot (A) and the Dalmar tendon support boot at resistance settings 1 (B), 2 (C) and 3 (D) (n = 7).

Fig 4: Mean ± s.e. support effect for gamgee bandage (A), modified Robert Jones bandage (B) and the palmar splint (C) (n = 7).

significant effect on the limb force-MCP joint angle relationship, and the modified Robert Jones distal limb bandage showed a significant effect only at high MCP joint angles of 245° (P<0.01; paired *t* test). The palmar splint provided significant support above 230° MCP joint extension. The Dalmar tendon support boot provided different levels of support at the different settings. Settings 1 and 2 provided significant support above 245° MCP joint extension and setting 3 provided significant support above 225° MCP joint extension.

Discussion

In vitro limb loading is a technique commonly used for predicting *in vivo* tendon function (Camp and Smith 1942; Kingsbury *et al.* 1978; Rooney *et al.* 1978; Shoemaker *et al.* 1991). The limb force-MCP joint angle relationship reported here is, however, different from that expected in a healthy horse. When using this loading system, the resistance to MCP joint extension provided by the bellies of the superficial and deep digital flexor tendons and the accessory ligament of the superficial digital flexor tendon are missing. Therefore, one would expect the MCP joint extension to be greater at any given limb force than that observed in a healthy horse *in vivo*. The limbs were loaded to a force of 10 N/kg body mass, which is similar to the vertical ground reaction force at a 3 m/s trot (Williams *et al.* 1999). However, a better guide for this loading system is the peak MCP joint angle during stance. Typical peak MCP joint angles are 216° at walk, 232° at trot, 228° lead canter, 238° nonlead canter and 250° at gallop (McGuigan 2001). These data, therefore, demonstrate that the splint and the Dalmar tendon support boot at setting 3 have protective effects at joint angles that would occur in a sound horse during low speed locomotion, and the modified Robert Jones bandage and Dalmar tendon support boot at settings 1 and 2 would be protective for a horse undertaking high-speed exercise. In a horse with palmar soft tissue injury, the joint would be hyperextended, increasing the amount of support provided at low speeds. However, neither the 2 conventional bandages nor the commercial exercise bandage provided any substantial resistance to extension of the MCP joint throughout the range of joint angles.
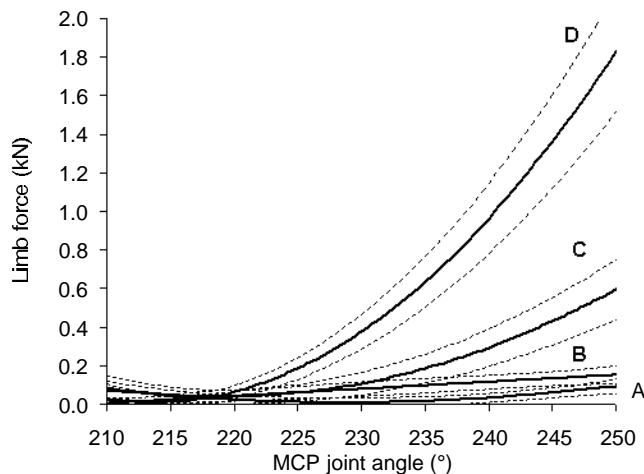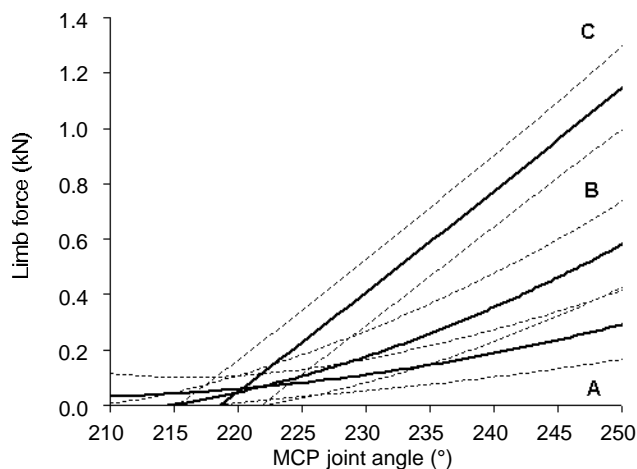
We have used the palmar contoured splint in 4 clinical cases, 3 of which had complete transection of the digital flexor tendons repaired surgically and cast postoperatively for 10–12 weeks. The splint was well tolerated by all horses. Splints were applied immediately after removal of the cast in the horses with tendon lacerations, before the animal could bear weight and combined with a caudal extension shoe in those cases with concurrent deep digital flexor tendon disruption. The splint was maintained in place for a minimum of 2 weeks with the limb remaining bandaged with the modified Robert Jones distal limb bandage subsequent to splint removal. The splints were made using the contralateral normal limb as a template in cases where the MCP joint was still overextended, since the joint angle of the leg where the splint is applied is critical in determining the degree of support provided. It is also possible to construct the splints in a normal horse and store them for application in clinical cases. If they are constructed in horses with relatively straight MCP joints, the splint may be more effective.

The Dalmar tendon support boot provided greater resistance to

MCP joint extension than the other support methods (Fig 3). The diverging plots at each of its 3 settings show that, as limb load/MCP joint angle increased the boot provided increasing degrees of resistance to MCP joint extension. The effectiveness of such a device suggests that it should be useful as adjunctive treatment of flexor tendon injury. The Dalmar tendon support boot can provide continuous support during rehabilitation from acute injury through convalescence and back to training. By means of its adjustment, it is possible to reduce gradually the amount of support the boot provides to the injured tendons as they heal. Furthermore, it can also provide support after cast removal in cases of tendon laceration or suspensory failure similar to the palmar splint, but with the added benefit of still allowing MCP joint mobility. As controlled mechanical loading is believed to improve tendon healing (Woo *et al.* 1981; Feehan and Beauchene 1990; Kubota *et al.* 1996), this device will enable animals to be brought back into light work earlier and potentially improve the quality of the healed soft tissues. The boot can be applied easily and removed at any time during the healing process, greatly simplifying examination and monitoring of the injured limb.

Unlike the palmar splint, the design of the Dalmar tendon support boot allows unrestricted flexion of the MCP joint so that it is suitable for use in exercising horses. This means that it may also be used to protect the flexor tendons from overstrain during exercise. The boots (at setting 1) have been fitted to 14 National Hunt horses undertaking routine gallop exercise for periods of 8–24 weeks by one of the authors (JTH). The boots were well tolerated by all horses, without any signs of damage to the underlying skin or associated structures. The boot puts pressure on the skin when loaded, but this will be intermittent rather than continuous and appears not to be an issue in trials to date. The low mass of the boot (200 g), which is similar to that of other exercise boots, means that it can be worn during exercise either as a support during rehabilitation of tendon injury or perhaps to guard against traumatic overstrain. At gallop, limb force will increase to about 1.3–1.5 x bwt and the design of the boot is such that, at its lowest settings, it provides increasing degrees of support as the joint angle increases. If so adjusted, the boot has minimal effect on tendon force and energy storage during normal galloping and, therefore, will not affect the normal motion of the horse. However, if the MCP joint hyperextends due to fatigue and incoordination, the boot would be predicted to resist the hyperextension, which may help to prevent tendon overstrain injury in horses in training.

In conclusion, this study demonstrated that the neoprene exercise boot and simple gamgee bandage had no significant effect on the limb force-MCP joint angle relationship and hence did not mechanically protect the digital flexor tendons from overstrain. The modified Robert Jones distal limb bandage with and without (only at high MCP joint angles) a contoured palmar splint, and the Dalmar tendon support boot both provided significant resistance to extension of the MCP joint and, consequently, would reduce the strain experienced by the SDFT, DDFT and suspensory ligament. The Dalmar tendon support boot can also be used in exercising horses, where it should provide continued mechanical protection of the flexor tendons throughout healing and rehabilitation.

Manufacturers' addresses

[1]Machine Mart Ltd., Nottingham, UK.
[2]Transducer World Ltd., Aylesbury, Buckinghamshire, UK.
[3]National Instruments, Newbury, Berkshire, UK.
[4]Microsoft Excel, Microsoft Corp., California, USA.
[5]Dalmar Ltd., Glanmire, Co.Cork, Ireland.
[6]Professional's Choice, Spring Valley, California, USA.
[7]Robinson Animal Healthcare, Chesterfield, UK.
[8]Smith and Nephew, Hull, Yorkshire, UK.
[9]Parema, Loughborough, Leicestershire, UK.
[10]3M, Manchester, Lancashire, UK.

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