Ena drives invasive macrophage migration in *Drosophila* embryos

Philippa K. Tucker¹, Iwan R. Evans¹ and Will Wood¹,*

**SUMMARY**

It is seldom the primary tumour that proves fatal in cancer, with metastasis the fundamental pathological process for disease progression. Upregulation of Mena, a member of the evolutionarily conserved Ena/VASP family of actin cytoskeletal regulators, promotes metastasis and invasive motility of breast cancer cells in vivo. To complement in vitro studies of Ena/VASP function in fibroblasts, we manipulated levels of Ena, the *Drosophila* homologue of Mena, in migrating embryonic macrophages (haemocytes). Consistent with data from fibroblasts in vitro, Ena localises to regions of actin dynamics within migrating haemocytes, stimulates lamellipodial dynamics and positively regulates the number and length of filopodia. However, whereas Ena overexpression in fibroblasts reduces migration speeds, overexpressing Ena in haemocytes leads to a dramatic increase in migration speeds, more closely resembling the increased motility of breast cancer cells that overexpress Mena. We provide evidence that this key difference is due to spatial constraints imposed on cells within the three-dimensional environment of the embryo; this might explain how Mena can be used to promote aggressive migratory behaviour during cancer progression.

**INTRODUCTION**

The metastasis of cancer cells from the primary tumour is the key step in cancer progression and requires invasive cell migration, a process also important during development (Hanahan and Weinberg, 2000; Franz et al., 2002). Actin polymerisation drives the formation of protrusions at the leading edge of a migrating cell, and adhesion of protrusions coupled with retraction and disassembly of adhesions at the rear of the cell enable continued migration. In many cell types, actin filaments are organised into broad, sheet-like lamellipodia, which consist of branched arrays of filaments at the leading edge, or are bundled into finger-like filopodial protrusions (Pollard and Borisy, 2003; Ridley et al., 2003). One actin-regulatory protein recently implicated in several human cancers is Mena (Di Modugno et al., 2004; Toyoda et al., 2009), a member of the Ena/VASP family (*Drosophila* Enabled, vasodilator-stimulated phosphoprotein) (Gertler et al., 1996), which antagonise capping of barbed ends of actin filaments, facilitating their continued elongation and stimulating cell protrusion (Bear et al., 2002).

Recent studies using rat breast carcinoma cells revealed that elevated levels of Mena increase cell motility in vivo and also metastasis to the lungs. Furthermore, overexpression of Mena increased invasive migration into collagen gels in vitro (Phillipar et al., 2008). Additionally, Ena/VASP proteins are targeted downstream of numerous guidance receptors (Bashaw et al., 2000; Evans et al., 2007; Lebrand et al., 2004), with the misregulation of many of these implicated in cancer (Brantley-Sieders et al., 2008; Kaufmann et al., 2009; Legg et al., 2008). Members of the Ena/VASP family are also regulated by the kinases Abl and PKC (Gertler et al., 1990; Wentworth et al., 2006), which are themselves heavily implicated in cancer progression (Mauro et al., 2010; Srinivasan et al., 2008).

Much of our understanding of Mena function is derived from studies of fibroblasts in vitro, where Ena/VASP proteins negatively regulate cell migration, potentially by antagonising capping at the barbed ends of actin filaments (Barzik et al., 2005; Bear et al., 2002). This activity is thought to facilitate actin polymerisation, enhancing the generation of actin-rich protrusions; however, in these cells exuberant Ena/VASP activity actually decreases migration speed because the protrusions formed are unstable and tend to be lost as membrane ruffles (Bear et al., 2000; Bear et al., 2002).

To determine how Ena/VASP proteins regulate cell migration in vivo, we have manipulated the levels of Ena, the *Drosophila* homologue of Mena (Gertler et al., 1996), within the macrophages (haemocytes) of developing embryos. Loss of zygotic Ena in *Drosophila* was initially shown to disrupt axon guidance (Wills et al., 1999). Subsequently Ena has been demonstrated to play an important role in embryonic morphogenesis, with removal of maternal and zygotic Ena disrupting processes such as germ band retraction, head involution and dorsal closure; during the latter, Ena regulates filopodial number and length as well as lamellipodial area in leading edge epithelial cells (Gates et al., 2007; Homem and Peifer, 2009). Furthermore, Ena plays important roles at the cortex of nurse cells during dumping and within border cells during their collective migration (Gates et al., 2009).

During *Drosophila* development, embryonic haemocytes undergo invasive and highly stereotyped migrations to distribute fully throughout the embryo and are capable of mounting rapid chemotactic and phagocytic responses to epithelial wounds and pathogens (Stramer et al., 2005; Tepass et al., 1994; Vlissidou et al., 2009; Wood et al., 2006). Here we have used time-lapse microscopy to visualise haemocytes as they migrate between the ventral nerve cord (VNC) and epidermis both during and after their developmental dispersal.

¹Department of Biology and Biochemistry, University of Bath, Bath BA2 7AY, UK
*Author for correspondence (w.wood@bath.ac.uk)

Received 17 March 2010; Accepted 11 August 2010

© 2011. Published by The Company of Biologists Ltd

This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial Share Alike License (http://creativecommons.org/licenses/by-nc-sa/3.0), which permits unrestricted non-commercial use, distribution and reproduction in any medium provided that the original work is properly cited and all further distributions of the work or adaptation are subject to the same Creative Commons License terms.
Similar to findings in fibroblasts in vitro, we show that Ena localises to sites of dynamic actin reorganisation in haemocytes in vivo. However, despite stimulating protrusion and lamellipodial dynamics in a similar fashion to that seen in fibroblasts, we find that Ena overexpression increases haemocyte migration speed, resembling the effect of Mena overexpression in cancer cells in vivo. We show evidence that a three-dimensional (3D) constraint in vivo prevents loss of protrusions as membrane ruffles, allowing a more concerted migration, which might also underlie the enhancement of cancer cell motility and metastasis upon Mena overexpression in vivo.

**RESULTS**

**Ena localises to regions of dynamic actin reorganisation in vivo**

Mena, a mammalian homologue of *Drosophila* Ena, typically localises to the tips of filopodia and leading edges of lamellipodia in cells such as fibroblasts and neurons in vitro (Gertler et al., 1996; Lanier et al., 1999). Ena itself is widely expressed within *Drosophila* embryos; levels are particularly high within the central nervous system (CNS) (Gertler et al., 1995) and the protein is also present within haemocytes (supplementary material Fig. S1A-C). To determine Ena localisation in vivo, Ena-GFP and mCherry-Moesin were co-expressed in *Drosophila* haemocytes using the GAL4-UAS system (Brand and Perrimon, 1993). At stage 15 of embryonic development Ena was enriched at the tips of filopodia and lamellipodia in haemocytes (Fig. 1A; supplementary material Movie 1). Time-lapse movies of filopodial extension and retraction revealed Ena at the tips of filopodia during extension, with retention at the tip in 25% of cases ($n=77$) during retraction (Fig. 1B); in the remainder Ena was lost from filopodial tips upon retraction (supplementary material Movie 1). Kymographic analysis of haemocytes in the embryo indicated that Ena was enriched at lamellipodial leading edges during extension but upon retraction this localisation was lost (Fig. 1C).

To investigate the distribution of Ena during directed migration, we analysed haemocytes undergoing lateral migration away from the ventral midline to the edges of the developing VNC, easily visualised in stage 14 embryos (Wood et al., 2006). Observation of laterally migrating haemocytes expressing Ena-GFP and mCherry-Moesin clearly showed that Ena localised to the leading edge of the lamellipodia during this directed migration (Fig. 1D,E; supplementary material Movie 2). Therefore, Ena is present at regions of dynamic actin reorganisation in migrating haemocytes in vivo and these locations are similar to those previously reported in both fibroblasts and neural growth cones in vitro (Gertler et al., 1996; Lanier et al., 1999).

![Fig. 1. Ena localises to the tips of filopodia and the leading edge of lamellipodia in vivo.](image-url) Haemocytes co-expressing Ena-GFP (green) and mCherry-Moesin (red) were imaged at stage 15 of embryonic development. (A) Ena-GFP localises to the tips of filopodia (arrowhead) and the leading edge of lamellipodia (bracket) in haemocytes at the midline. (B) Ena-GFP at a filopodial tip during extension and retraction (see supplementary material Movie 1 for an example of Ena-GFP being lost during retraction). (C') Kymograph generated along the axis of protrusion (solid line in C), demonstrating the presence of Ena-GFP at the leading edge during lamellipodial extension and its loss from this site upon retraction (arrowheads); the dotted line indicates the time point in the kymograph corresponding to the still image in C. (D) Ena-GFP is present at the lamellipodial leading edge during lateral migration (see supplementary material Movie 2 for corresponding time-lapse). Dots and lines reveal progress of the haemocyte when moving from the midline to the edge of the VNC. (E) Images showing the GFP channel of the haemocyte from D; in these images Ena-GFP is clearly localised at the lamellipodial leading edge (arrowheads). Scale bars in C represent 2 μm (vertical) and 60 seconds (horizontal); all other scale bars represent 10 μm.
Ena regulates macrophage speed in vivo

Ena regulates the formation and dynamics of both filopodia and lamellipodia in vitro (Applewhite et al., 2007; Bear et al., 2002), and we sought to determine what effect Ena has on these structures within haemocytes. To this end, Ena or FP4Mito-GFP (FP4Mito) (Gates et al., 2007) were specifically overexpressed in haemocytes to supplement or inactivate Ena function, respectively. FP4Mito has previously been shown to phenocopy genetic ablation of Ena/VASP function via sequestration of endogenous Ena at mitochondria away from sites of actin dynamics (Bear et al., 2000; Gates et al., 2007) and did so efficiently in haemocytes (supplementary material Fig. S1A). FP4Mito and Ena were co-expressed with cytoplasmic GFP to detail haemocyte morphology. Typically, wild-type haemocytes produced large lamellipodia, from which numerous filopodia protrude (Fig. 2B), whereas very few filopodia were produced when Ena was inactivated by expression of FP4Mito, with residual filopodia drastically shortened (Fig. 2A,D,E; Table 1). By contrast, Ena overexpression increased both the number and length of filopodia (Fig. 2C,E; Table 1).

Whereas Ena exerted striking effects on filopodia, its regulation of lamellipodia was more subtle. Ena was not required to form lamellipodia because these structures remained after its inactivation (Fig. 2A) and intriguingly both overexpression and inactivation of Ena increased average lamellipodial area (Fig. 2F; Table 1). Instead Ena regulated lamellipodial dynamics: Ena inactivation led to stable lamellipodia that fluctuated very little in area over time when compared with the more dynamic lamellipodia of wild-type haemocytes. Consistently, overexpression of Ena increased lamellipodial dynamics compared with wild-type cells (Fig. 2A-C,G; Table 1). To determine how Ena regulates dynamics at the level of individual lamellipodia, we carried out kymography on specific lamellipodial regions in single cells. Kymographs showed that wild-type lamellipodia protruded and retracted at regular intervals (Fig. 2I); Ena inactivation decreased the speed of lamellipodial protrusion and prolonged the persistence of these protrusions (Fig. 2H,K,L; Table 1), whereas Ena overexpression increased lamellipodial protrusion speeds but these faster-growing protrusions were less persistent (Fig. 2J-L; Table 1).

Overexpression of Ena increases haemocyte speed in vivo

Our findings regarding lamellipodial dynamics are consistent with results from fibroblasts in vitro, where Ena overexpression has been shown to increase rates of lamellipodial protrusion but decrease persistence, translating to an overall reduction in the speed of migration (Bear et al., 2000). This negative effect on migration speed is difficult to reconcile with recent data suggesting that cancer cells with elevated levels of Mena display a higher propensity to metastasise (Philippar et al., 2008), which would be consistent with a positive effect on migratory speed. In light of this apparent paradox we wondered how Ena upregulation in vivo might affect the overall speed of haemocyte migration in a variety of contexts, given that lamellipodial dynamics in haemocytes in vivo seem to be regulated in a similar Ena-dependent manner to fibroblasts in vitro.

We began by looking at lateral migration of haemocytes, an example of a highly stereotyped, directed migratory process (Fig. 3A). Live analysis of individual haemocytes revealed that Ena overexpression increased speed compared with wild-type haemocytes during lateral migration, whereas Ena inactivation reduced migration speed (Fig. 3E; Table 1). A similar decrease in lateral migration speed was observed in ena mutant embryos.
Ena regulates macrophage speed in vivo

RESEARCH REPORT

Ena regulates macrophage speed in vivo (supplementary material Fig. S1D). Surprisingly, neither Ena inactivation nor overexpression affected directionality (compare Fig. 3B-D), suggesting Ena controls cell speed independently of signalling events required to direct this migration. Furthermore, it implies that filopodia might not be crucial in sensing lateral cues or mechanically in lateral migration itself, given that Ena inactivation significantly reduced filopodial numbers.

Haemocytes also migrate in a directed fashion towards laser-induced, epithelial wounds in response to H2O2 production (Moreira et al., 2010; Stramer et al., 2005). Tracking haemocyte migration for an hour post-wounding, we found that Ena overexpression increased haemocyte speed towards wounds, whereas inactivation reduced speed compared with wild-type controls (Fig. 3F-J; Table 1). Interestingly, neither overexpression nor inactivation of Ena affected haemocyte directionality towards wounds (compare Fig. 3G-I), nor wound healing itself, although inactivating Ena did slightly reduce the number of haemocytes recruited to wounds [eight haemocytes for wild type (n=35) compared with seven for FP4Mito (n=45); P=6.04 × 10^-6].

The fact that Ena overexpression increased the rate of two distinct examples of directed migration in vivo whereas inactivation decreased migration speed is in stark contrast to similar experiments conducted with fibroblasts in vitro. However, fibroblast speed was measured during random migration. We

![Fig. 3. Ena positively regulates haemocyte migration speed in vivo.](https://example.com/fig3)

**Table 1. Ena-dependent regulation of haemocyte morphology and behaviour in vivo**

<table>
<thead>
<tr>
<th>Expression</th>
<th>Filopodia</th>
<th>Lamellipodia</th>
<th>Migration speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Length (µm)</td>
<td>Change in area (µm²)</td>
</tr>
<tr>
<td>FP4Mito</td>
<td>0.13</td>
<td>1.6</td>
<td>380 (1.7×10^-20)</td>
</tr>
<tr>
<td>WT</td>
<td>4.9</td>
<td>2.9</td>
<td>330 (0.0021)</td>
</tr>
<tr>
<td>Ena</td>
<td>7.8</td>
<td>4.0</td>
<td>380 (2.1×10^-3)</td>
</tr>
</tbody>
</table>

All values are averages, with P-values shown in parentheses if applicable.
Disease Models & Mechanisms

Ena regulates macrophage speed in vivo

probably monitored migration of haemocytes at stage 15 of development, when they too migrate randomly on the ventral side of the embryo (Fig. 3K,M). Manipulation of Ena caused no obvious differences in haemocyte trajectories but, consistent with wounding studies, Ena overexpression increased haemocyte speed whereas inactivation reduced it (Fig. 3L-O; Table 1).

Spatial constraints might underlie behavioural differences in vivo and in vitro

Using three distinct in vivo migration assays we have shown that, in contrast to fibroblast migration in vitro, Ena positively regulates migration speed. This finding is relevant to cancer studies given the fourfold upregulation of Mena in rat breast carcinoma cells (Wang et al., 2004), which increases their motility and invasiveness (Philippar et al., 2008). This discrepancy might occur because protrusions created by Ena-overexpressing fibroblasts are frequently lost as ruffles in vitro (Bear et al., 2002); in contrast, in vivo cells are constrained by their 3D environment (Fig. 4D) (Evans et al., 2010), which might physically prevent ruffling, allowing protrusions to be used productively during cell migration and lead to increased cell speeds.

In order to investigate this further, we expressed mCD8-GFP to label the plasma membrane of haemocytes and observed their dynamic behaviour in vivo and in vitro. In vivo haemocytes never formed membrane ruffles as they migrated through the embryo (Fig. 4A; supplementary material Movie 3). However, distinctive wave-like ruffles were seen forming at the leading edge of lamellipodia and moving centripetally towards the cell body when mCD8-GFP-expressing haemocytes were cultured in vitro (Fig. 4B; supplementary material Movie 3). Strikingly, on addition of methylcellulose to thicken cell culture media and reconstitute a physical constraint, haemocytes no longer formed membrane ruffles in vitro (Fig. 4C; supplementary material Movie 3), more closely resembling haemocytes in vivo. Indeed, kymographic analysis of lamellipodial dynamics revealed no significant difference in speed or persistence of lamellipodial protrusions between wild-type haemocytes in vivo and those in vitro with methylcellulose (supplementary material Table S1). However, protrusions were less persistent in vitro without methylcellulose compared with in vivo, and speed of lamellipodial protrusion was increased (supplementary material Table S1). This suggests that protrusions are less stable in vitro than in vivo and that the addition of a physical constraint that prevents ruffling stabilises protrusions in a manner similar to the in vivo environment.

We then compared the dynamics of protrusions that are lost as membrane ruffles to those lost without ruffling in vitro and found that protrusions lost as ruffles had a faster speed of retraction and retracted for longer. We also found that the overall frequency of retraction in vitro was much higher than in vivo (supplementary material Table S1), with retraction events coincident with membrane ruffles accounting for 58% of retraction events. Taken together these events demonstrated that in the absence of a 3D constraint protrusions are less persistent and retraction events more severe. The stabilisation of protrusions and inhibition of membrane ruffling thus enables efficient migration in vivo, because membrane ruffling impacts negatively on migration by increasing both the speed and persistence of lamellipodial retraction. Consistently, the in vivo environment was sufficient to inhibit membrane ruffling on overexpression of active Rac (Fig. 4E; supplementary material Movie 4), which is known to induce ruffling in vitro (Ridley et al., 1992); Rac overexpression led to the formation of exuberant
Ena regulates macrophage speed in vivo

discussion

Here we demonstrate that Ena increases the speed of lamellipodial protrusion but reduces the persistence of these protrusions in haemocytes in vivo, paralleling the role of Mena in fibroblasts cultured in vitro (Bear et al., 2002). However, despite regulating lamellipodial dynamics similarly, Ena overexpression increased haemocyte migration speeds in vivo, whereas it reduces fibroblast speeds in vitro (Bear et al., 2000). Consistent with our findings, Ena inactivation in border cells also decreased their migration speeds (Gates et al., 2009). Interestingly, our in vivo haemocyte data closely correlate with the finding that Mena upregulation in rat breast carcinoma cells increases metastasis and invasion (Philippar et al., 2008). Furthermore, we show that the external environment plays a key role in determining haemocyte migration speeds, potentially by placing spatial constraints on haemocytes that inhibit membrane ruffling. Correspondingly, when haemocytes were cultured in vitro they began to produce membrane ruffles, but application of an artificial constraint blocked membrane ruffling. Although we observed retraction events in vivo, these events were less severe and occurred less frequently during migration; therefore, the inhibition of ruffling enables lamellipodia to advance further and in doing so increase cell migration speed. Our results might be particularly pertinent to invasive migration of cancer cells through stromal tissue in which extracellular matrix is highly constractive (Wolf et al., 2007). Overexpression of Mena might therefore be advantageous for invasion in this spatially restricted microenvironment because protrusions that might otherwise be lost as membrane ruffles could be rendered competent to contribute to cell migration.

It has been suggested that levels of membrane ruffling in combination with adhesion strength might underlie differing migration speeds between cell types (Small et al., 2002). The spatial constraints imposed on migrating haemocytes could restrict the detachment of Ena-regulated lamellipodia from their adhesions to the substrate, enabling faster migration. Alternatively, Ena could assume a more direct role in modulating adhesion as Mena localises to focal contacts and adhesions in fibroblasts (Gertler et al., 1996). However, selective removal of Mena from adhesions did not affect cell migration speed in fibroblasts (Bear et al., 2000). Integrins are clearly important for haemocyte migration in vivo (Siekhaus et al., 2010; Huelsmann et al., 2006; Urbano et al., 2009), but the nature of adhesions made by these cells has yet to be addressed and Ena-positive, focal-adhesion-like structures do not seem to be present. Furthermore, a GFP-tagged version of integrin-linked kinase, a kinase that associates with integrins at adhesion sites (Zervas et al., 2001), did not localise to adhesion-like puncta within haemocytes (data not shown). It will be intriguing to see exactly what types of adhesive structures haemocytes make and whether there is a relationship between Ena levels and integrins as observed in epithelial cells (Delon and Brown, 2009). We cannot rule out disruption of adhesions on overexpression of Ena or FP4Mito, although any such effect would be relevant to misregulation of Ena/VASP levels given the reduction in migratory speeds in both ena mutants and embryos containing FP4Mito-expressing haemocytes.

In this study we show that Ena overexpression and inactivation increase total lamellipodial area. A similar increase in lamellipodial area is seen in Drosophila leading edge epithelial cells upon Ena overexpression; however, inactivation of Ena reduces lamellipodial area in these cells (Homem and Peifer, 2009), implying Ena has some cell-type-specific effects, most probably dependent upon the levels and activities of other actin regulatory proteins within the cell. In addition to lamellipodial area, we demonstrate that Ena regulates filopodial number and length in haemocytes in vivo; a similar role for Ena has been observed in epithelial cells and neurons (Gates et al., 2007; Lebrand et al., 2004), reiterating the importance of Ena for efficient initiation and elongation of filopodia. However, Ena inactivation did not totally preclude the formation of filopodia in haemocytes, suggesting that Ena-independent filopodia can be produced by other actin-regulatory proteins in these cells. One candidate for this role is the formin Diaphanous (Dia), because this protein is thought sufficient to initiate filopodial formation (Block et al., 2008; Steffen et al., 2006) and a similar Dia-regulated compensatory mechanism was recently demonstrated in leading edge epithelial cells during dorsal closure upon Ena inactivation (Homem and Peifer, 2009). Dia is expressed in haemocytes and much, but not all, endogenous Dia was recruited in an Ena-dependent fashion to mitochondria upon expression of FP4Mito and co-localised with Ena-GFP at filopodia, raising the possibility that Ena might be required to target Dia to sites of dynamic actin rearrangement (supplementary material Fig. S3A–E). Nonetheless, the comparable reduction in migration speeds observed in FP4Mito-expressing haemocytes and in ena mutants indicates that the effects of FP4Mito are specific to Ena. We cannot, however, rule out a role for Dia in concert or downstream of Ena, although zygotic dia mutants failed to show a significant reduction in lateral migration speeds (supplementary material Fig. S3F). Further analysis of the role of Dia and its crosstalk with Ena will illuminate how haemocytes form appropriate protrusions for migration in vivo.

This work demonstrates the importance of investigating cell migration in vivo, and highlights the role that the surrounding environment can exert on invasive migration. Indeed, we reveal that disrupting one actin regulatory protein can have drastically different effects on in vitro and in vivo migration. Recent work has shown dramatic differences in the migration machinery operating within mammalian leukocytes as they migrate through different environments, with an absolute requirement for integrins...
in vitro but no requirement for these proteins during their interstitial migration in vivo (Lammermann et al., 2008). It is therefore becoming increasingly important to develop systems in which researchers can study cell migration in the complex setting of a living organism. Haemocytes represent such a system, as they undergo stereotyped migrations in response to a variety of stimuli, allowing the contributions of actin regulators to be probed in several different circumstances and within a genetically tractable animal. Here we have used these cells to understand how Ena functions to promote cell motility in vivo, mirroring its pro-migratory role during metastasis. Similarly, Fascin, another actin regulatory protein implicated in cancer invasiveness, was also recently demonstrated to be important in mediating haemocyte migration (Zanet et al., 2009). Further studies using these cells will lead to a better understanding of cell migration in vivo and in doing so could provide insight into how misregulation of the actin cytoskeleton might contribute to metastasis and tumour progression.

**METHODS**

**Fly stocks**

SerpentHemoGAL4 (srpGAL4) (Bruckner et al., 2004) and croquemortGAL4 (crqGAL4) (Stramer et al., 2005) were used to drive expression of UAS constructs specifically in haemocytes. The following UAS constructs were used in this study (obtained from Bloomington Stock Center unless otherwise stated): UAS-Ena-GFP, UAS-FPPPPmito-GFP (both obtained from M. Peifer, Chapel Hill) (Gates et al., 2007), UAS-mCherry-Moesin (obtained from P. Martin, University of Bristol) (Millard and Martin, 2008), UAS-mCD8-GFP (Lee and Luo, 1999), UAS-Ena (Ahern-Djamali et al., 1998) and UAS-Rac12 (Luo et al., 1994). The constructs and drivers were used to produce the following genotypes: w;srpGAL4,UAS-mCherry-Moesin;UAS-Ena-GFP and w;srpGAL4,UAS-mCD8-GFP flies were generated to probe Ena localisation and membrane ruffling, respectively; wsrpGAL4,UAS-GFP;crqGAL4,UAS-GFP (wild type, WT), wsrpGAL4,UAS-GFP/+;crqGAL4,UAS-GFP;UAS-FPPPPmito-GFP (Ena inactivation, FP4Mito) and wsrpGAL4,ias-GFP/+;crqGAL4,UAS-GFP;UAS-Ena (Ena overexpression, Ena) embryos were used for morphology, migration and injection studies; wsrpGAL4,UAS-GFP/+;crqGAL4,UAS-GFP;UAS-Rac12 embryos were used to investigate ruffling in vivo; finally, enaGC1 (Gertler et al., 1995), ena23, ena10 (Ahern-Djamali et al., 1998), dia2 or dia2 (Castrillon and Wasserman, 1994) homozygous embryos with GFP-labelled haemocytes were generated by selecting CTG-negative embryos from a stable stock of mutant/CTG;srpGAL4,UAS-GFP.

**Live imaging**

Embryos were prepared for imaging as previously described (Wood and Jacinto, 2005) and imaged live on a Zeiss LSM510 confocal microscope using Zeiss fluar 40×/1.3 oil DIC, plan-apochromat 63×/1.4 oil and c-apochromat 63×/1.2 water immersion objectives at the Bath BiolImaging Facility. The resulting stills and time-lapse movies were assembled and analysed using ImageJ (NIH).

**Cell migration assays**

For the wound assay the epithelium of stage 15 embryos was ablated dorsolaterally with respect to the VNC with a nitrogen laser-pumped dye laser (model no. VSL-337ND-S; Laser Science Inc.) as previously described (Wood et al., 2002). Haemocyte migration was then imaged live for 1 hour post-wounding. For live imaging of lateral migration and random motility of haemocytes, embryos were mounted ventral side up and imaged live from stage 14 or stage 15, respectively.

**In vitro haemocyte culture**

Ten stage 15 embryos were dechorionated and bled into a drop of 10% fetal bovine serum (FBS; Sigma) in S2 cell media (Sigma) ±0.8% methylcellulose (Sigma) inside a Nunclon A-coated 60 mm tissue culture dish (Nunc). A coverslip was then placed on top and sealed using nail varnish. Haemocytes were allowed to adhere for 60 minutes at room temperature before live imaging through the coverslip.

**In vitro staining of haemocytes**

For supplementary material data, stage 15 embryos of each genotype were dechorionated and dissociated by repeated pipetting in 125 µl of 10% FBS (Sigma) in S2 cell media (Sigma). (WT and FP4 haemocytes in the supplementary material are the same...
Disease Models & Mechanisms
to retraction phase) of lamellipodial protrusion. Kymographic
positive gradients) and persistence (period of protrusion prior
dynamics and filopodial dynamics. The multiple kymograph
classified as filopodia. A minimum of five haemocytes were
quantified using the line tool, with protrusions >1
time point over a 25 minute period. Filopodial length was
total cell area (each parameter was measured manually) for each
from three embryos. To measure fluctuations in lamellipodial
coordinates used to calculate speed. When determining cell
the cell body being tracked was highlighted manually, and its
injection, coverslips were attached as per normal live imaging and
injected anteriorly with 2.5 mg/ml rhodamine-conjugated 70 kDa
for 4 minutes prior to covering with voltalef oil. Embryos were then
as described above, but were dried in a box containing silica gel
for 2 hours in a humidified chamber at room temperature.
coated 60 mm tissue culture dish (Nunc) and cells were allowed to
adhere for 2 hours in a humidified chamber at room temperature.
After 2 hours, the medium was removed and cells fixed with 4%
parafomaldehyde (Sigma) made up in PBS. Adherent cells were
permeabilised by washing twice in 0.1% Triton-X 100 (Sigma) in
PBS. Rabbit anti-Dia (Afshar et al., 2000; a gift from M. Peifer, UNC, Chapel Hill) and mouse 5G2 anti-Ena (Bashaw et al., 2000)
[supernatant obtained from Developmental Studies Hybridoma Bank, University of Iowa (DSHB)] were used at 1:5000 and 1:50,
respectively. Goat anti-rabbit Alexa-Fluor-568 and goat anti-mouse
Alexa-Fluor-598 (Molecular Probes; both diluted 1:200) were used
to detect primary antibodies. PBS washes were performed between
each incubation, and stained cells mounted in mowiol (Calbiochem)
with a coverslip placed on top. Stained cells were imaged on the
Zeiss LSM510 confocal microscope, with residual GAL4-driven
GFP fluorescence used to identify haemocytes.

To determine whether Ena was required for localisation of Dia
to FP4Mito, embryos with FP4Mito-labelled haemocytes from an
ena^{GCl/CyO;CyaGAL4aas;FP4Mito/+} lagey cage were dissected in
250 ml of media and then split between two tissue culture dishes.
One dish was stained for Dia to probe its recruitment to FP4Mito-
GFP-positive mitochondria, and the other for Ena to detect the
presence of ena^{GCl} homozygotes in the culture on the basis of
absence of Ena at mitochondria.

Dye injections
Stage 15 embryos were prepared for live imaging ventral side up
as described above, but were dried in a box containing silica gel
for 4 minutes prior to covering with volatolaf oil. Embryos were then
injected anteriorly with 2.5 mg/ml rhodamine-conjugated 70 kDa
dextran (Molecular Probes), using Femtotips II and a FemtoJet/InjectMan injection system (Eppendorf). Following injection,
coverslips were attached as per normal live imaging and
the position of haemocytes relative to extracellular space, as
marked by the injected rhodamine-dextran, was followed live.

Image analysis and quantification
All analysis was performed using ImageJ. Cell tracking was performed using the manual tracking plugin on maximum
projections of five slices (representing a depth of 20 μm on the
ventral side of each embryo). For each time point the centre of
the cell body being tracked was highlighted manually, and its
coordinates used to calculate speed. When determining cell
migration speeds a minimum of 30 haemocytes were measured
from three embryos. To measure fluctuations in lamellipodial
area through time, the cell body area was subtracted from the
total cell area (each parameter was measured manually) for each
time point over a 25 minute period. Filopodial length was
quantified using the line tool, with protrusions >1 μm long
classified as filopodia. A minimum of five haemocytes were
analysed from three embryos when analysing lamellipodial
dynamics and filopodial dynamics. The multiple kymograph
plugin was used to generate kymographs (Hinz et al., 1999),
which were in turn used to quantify the rate (calculated from
positive gradients) and persistence (period of protrusion prior
to retraction phase) of lamellipodial protrusion. Kymographic
analysis was undertaken on six or more haemocytes from over
five different embryos.

Data was plotted in ‘box and whisker’ plots; whiskers
correspond to the 10th and 90th percentiles, the box corresponds
to the lower and upper quartiles, and the line shows the position of
the median.

ACKNOWLEDGEMENTS
We thank Brian Stramer (KCL), Paul Martin (University of Bristol), Mark Peifer (UNC, Chapel Hill) and the Bloomington Stock Center for generously providing fly stocks. W.W. is funded by a Wellcome Trust Senior Research Fellowship; P.K.T. is supported by a BBSRC studentship.

COMPETING INTERESTS
The authors declare no competing financial interests.

AUTHOR CONTRIBUTIONS
P.K.T. and I.R.E. carried out the experiments; P.K.T., I.R.E. and W.W. designed and interpreted the experiments and prepared the manuscript.

SUPPLEMENTARY MATERIAL
Supplementary material for this article is available at

REFERENCES
Ahern-Djamali, S. M., Comer, A. R., Bachmann, C., Kastenmeier, A. S., Reddy, S. K.,
enabled and rescue by human vasodilator-stimulated phosphoprotein (VASP)
indicate important functional roles for Ena/VASP homology domain 1 (EVH1) and
Applewhite, D. A., Barzik, M., Kojima, S., Svittina, T. M., Gertler, F. B. and Borisy, G. G.
(2007). Ena/VASP proteins have an anti-capping independent function in
Barzik, M., Kotova, T. I., Higgs, H. N., Hazelwood, L., Hanein, D., Gertler, F. B. and
presence of barbed end capping proteins. J. Biol. Chem. 280, 28653-28662.
axon guidance: Abelson and Enabled play opposing roles downstream of the
Bear, J. E., Loureiro, J. J., Libova, I., Fassler, R., Weihland, J. and Gertler, F. B.
Bear, J. E., Svittina, T. M., Krause, M., Schafer, D. A., Loureiro, J. J., Strasser, G. A.,
between Ena/VASP proteins and actin filament capping regulates fibroblast motility.
Cell 99, 509-521.
Block, J., Stradal, T. E., Hanisch, J., Jefferfs, R., Kostler, S. A., Urban, E., Small, J. V.,
J. Microsci. 231, 506-517.
cell fates and generating dominant phenotypes. Development 118, 401-415.
Brantley-Sieders, D. M., Zhuang, G., Hicks, D., Fang, W. B., Hwang, Y., Cates, J. M.,
Coffman, K., Jackson, D., Bruckheimer, E., Muraoka-Cook, R. S. et al. (2008). The
receptor tyrosine kinase EphA2 promotes mammary adenocarcinoma tumorigenesis
Bruckner, K., Kochek, L., Duchek, P., Luque, C. M., Rorth, P. and Perrimon, N.
in Drosophila and shares domains of similarity with the products of the limb
deformity gene. Development 120, 3367-3377.
Di Mulino, F., Bronzi, G., Scanlan, M. J., Del Bello, D., Cascioli, S., Venturo, I.,
protein, a serex-defined antigen overexpressed in breast cancer eliciting both
humoral and CD8+ T-cell immune response. Int. J. Cancer 109, 909-918.
mediate repulsion from ephrin ligands. J. Cell Sci. 120, 289-298.


<table>
<thead>
<tr>
<th>Condition</th>
<th>Rate of Protrusion (μm/min)</th>
<th>Persistence of Protrusion (mins)</th>
<th>Rate of Retraction (μm/min)</th>
<th>Persistence of Retraction (mins)</th>
<th>Frequency of Retraction Events (events/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in vivo average</td>
<td>5.3</td>
<td>0.32</td>
<td>3.3</td>
<td>0.44</td>
<td>1.0</td>
</tr>
<tr>
<td>in vivo p value</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>in vitro average</td>
<td>10</td>
<td>0.0076</td>
<td>9.0</td>
<td>0.32</td>
<td>1.6</td>
</tr>
<tr>
<td>in vitro p value</td>
<td>1.1×10^{-5}</td>
<td>0.0077</td>
<td>1.8×10^{-5}</td>
<td>0.020</td>
<td>0.0052</td>
</tr>
<tr>
<td>in vitro with methylcellulose</td>
<td>3.9</td>
<td>0.26</td>
<td>3.3</td>
<td>0.35</td>
<td>1.1</td>
</tr>
<tr>
<td>in vitro with methylcellulose p value</td>
<td>0.086</td>
<td>0.085</td>
<td>0.93</td>
<td>0.08</td>
<td>0.85</td>
</tr>
</tbody>
</table>